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Building Information Modeling for Managing Design and Construction
Assessing Design Information Quality

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Publication date:
2012

Document Version
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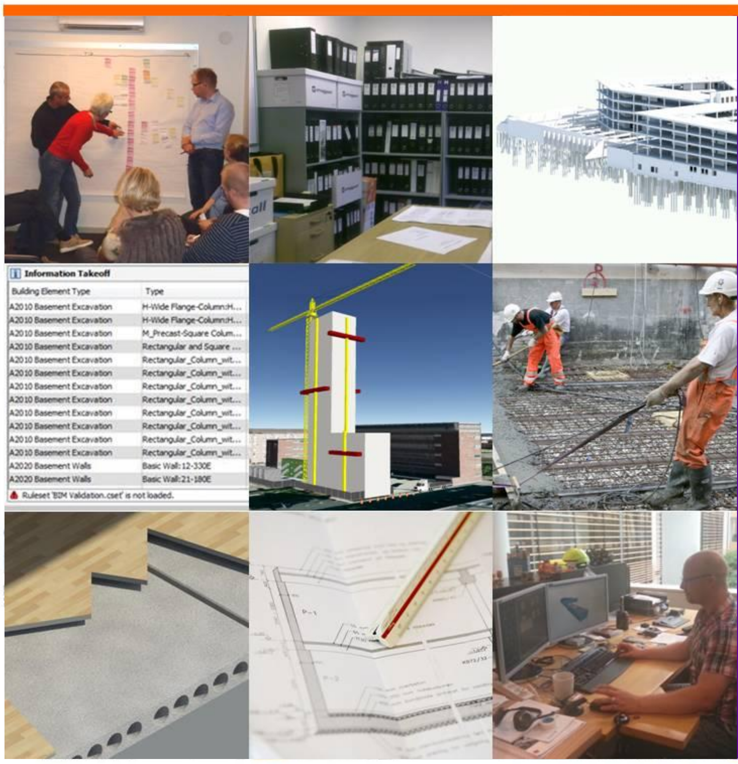

Ole Berard

PhD Thesis

Department of Civil Engineering

2012

DTU Civil Engineering Report R-272 (UK)
October 2012

DTU Civil Engineering
Department of Civil Engineering

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Report R-272
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By
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Cover photo:	Courtesy of MT Hojgaard (upper right, middle right, lower center), by author (rest)
Published by:	Department of Civil Engineering, Brovej, Building 118, DK-2800 Kgs. Lyngby, Denmark
Request report from:	www.byg.dtu.dk
ISSN:	[1601-2917]
ISBN:	[978-87-7877-354-8]

Überall geht ein früheres Ahnen dem späteren Wissen voraus.

[Earlier intuition always precedes later knowledge.]

Friedrich Wilhelm Heinrich Alexander Freiherr von Humboldt (September 14, 1769–May 6, 1859)

Preface

This thesis is submitted to the Department of Civil Engineering at the Technical University of Denmark in partial fulfillment of the requirements for the degree of doctor of philosophy. The study was conducted as an industrial PhD project[1] between May 2009 and July 2012. The principal advisor was Associate Professor Flemming Vestergaard, DTU Civil Engineering; the co-advisor was Associate Professor Jan Karlshoej, DTU Civil Engineering; company advisor was Head of Section Lars Fuhr Pedersen, MT Højgaard. Professor Martin Fischer, Civil and Environmental Engineering at Stanford University, hosted an external research stay between January and June 2011. The dissertation is paper-based and consists of the present thesis and the papers prepared during the study (see the List of Papers).

Søborg, July 2012

Ole Berard
PhD Student

[1] An industrial PhD project is a three-year industrially focused PhD project in which the student is hired by a company while also being enrolled at a university at the same time. For more information, see http://en.fi.dk/funding/funding-opportunities/industrial-phd-programme.

Foreword

Most construction projects are unique. Many factors, including demand for different architectures, development of technologies, demand for sustainability, different local building codes, local geographical and geotechnical conditions, require that every construction project be designed in a different way each time.
This is the most significant difference between the construction industry and other manufacturing industries. In the construction industry, we design and build new facilities every time and our major challenge is to control the design process and the corresponding deadlines.
Construction companies have high expectations regarding the design and, not least, the design quality that ensures that essential high-quality information is available just-in-time and ready for the craftsmen and constructions managers on- site through the entire construction process.
Unfortunately, the reality is that there is often either too much information to maintain an overview or not enough to be able to achieve excellent performance in time during the construction process.
The quality of the information is often poor and difficult to locate, with various pieces of information in several different drawings. While clashes between building systems, both the physical and in the design, should be non-existent or very rare in construction projects, unfortunately they are actually quite frequent.
The deficiencies are not only caused by the designers. The design process involves many participants and has become increasingly complex.
Information from the construction managers regarding constructability, economy, and schedule is important for selecting the right design. Information from material suppliers, subcontractors, authorities, and sub-designers is integrated into the overall design and, as the information is inter-dependent, the level of complexity is increasing. Instead of being passive receivers of design information, the subcontractors and suppliers are more often the suppliers of the design information required to perform their own work and co-responsible for the design coordination.
Clearly, construction companies and the entire construction industry have to do something to mitigate the consequences of the design complexity on the quality, the economy, and the schedules of the construction projects. One option is to make the design process much more transparent for the participants in order to be able to quickly check progress and correct errors; another important issue is to be able to measure whether the design is ready for construction.
The present PhD project's attempt to describe and measure the design information quality is a vital and important step towards a better and more transparent design in a high-quality lean design process that will provide major benefits to the construction projects in MT Hojgaard and in the construction industry.
Therefore, the relevance of the project cannot be overestimated. Over the past three years, we have participated in a very exciting and challenging creation process and we are now we are eager to implement the results.

Lars Fuhr Pedersen
Head of section and company advisor
MT Højgaard A/S

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English Abstract

Contractors planning and executing construction work encounter many kinds of problems with design information, such as uncoordinated drawings and specification, missing relevant information, and late delivery of design information. Research has shown that missing design information and unintended outcomes, such as building defects, schedule delays, and budget overruns are related. Research in other fields indicates a relationship between information management and the performance and efficiency of organizations. This has led to the assumption that better information will eventually lead to a better outcome of construction work. Even though contractors regularly encounter design information problems, these issues are accepted as a condition of doing business and better design information has yet to be defined.

Building information modeling has the inherent promise of improving the quality of design information by suggesting technologies and methods that are supposed to improve design information. However, building information modeling provides no means to assess these improvements of design information.

This research introduces design information quality as an equivalent to information quality in the field of information systems. Design information quality is defined as *conformance of the design information supplied by the design team to a contractor's specifications for the planning and execution of a construction project*.

The following eight criteria have been identified in order to describe design information quality:

- **Relevance –** scope, sequence, and time-frame of the information delivery
- **Consistency –** the coordination of design information, with respect to geometry, functional requirements, and compliance with standards and regulations.
- **Correctness –** extent of missing, incorrect, or outdated design information.
- **Precision –** accurate geometry and unambiguous requirements for the scope.
- **Availability –** effort to securely access current design information.
- **Distribution –** effort to manage, share, and route design information.
- **Flexibility –** effort to transform, extract, or update information for work tasks.
- **Amount of Information** – the number of documents and files, and other media, should be appropriate for the scope.

The criteria were identified by empirical studies and theory on information quality in the architectural, engineering and construction (AEC) industry and other fields. Empirical research was conducted to understand the design information problems that contractors (information consumers) encounter. The problems were identified by observations and interviews made in 12 organizations.

One prerequisite for improving design information quality is the ability to identify and specify information requirements for the task at hand. Requirements can only be fulfilled if they are explicit. Information requirements are task-dependent, and because AEC projects are perceived as unique, they often also depend on the project, person, and time in the project. Hence, the work flow and, consequently, the information flow are unique. Therefore, the present study suggests a method for identifying information requirements collaboratively between the design and the construction team. The method is based on pull scheduling for design from lean construction. Furthermore, the study suggests the adoption of information delivery manuals for documentation of the information requirements.

Apart from identifying the criteria, the research also describes observable phenomena in order to assess each criterion. A scale is suggested to score each criterion based on the current practice. The scale consists of five points, ranging from traditional to most innovative practice. However, since technology and practice changes rapidly, the definition of each score has to be adjusted regularly.
Finally, the framework is applied to a construction project in order to evaluate its practical application. The framework provides meaningful measures on the improvement of the design information quality during the project and identifies areas with low design information quality for further improvement and investigation.
Naturally, the framework must mature through its application in research and practice. Nonetheless, it does provide the means for practice to articulate problems in design information quality in order to eventually make design information quality an area of competition. It also allows practice to assess the effect technology and process improvements that are supposed to affect design information quality. Practice can also use the framework to evaluate the risk of low information quality. Research can use the framework to identify the relation of design information quality and positive or negative outcomes; for example, with respect to building defects, schedule, and cost conformance.

Danish Abstract

Entreprenører oplever en række problemer med design information, når de planlægger og udfører byggeprojekter, som f.eks. ukoordinerede tegninger og beskrivelser, manglende eller forsinket levering af relevante designinformationer. Forskning har vist, at manglende designinformation og utilsigtede resultater, som byggeskader, forsinkelser og budgetoverskridelser hænger sammen. Forskning i andre områder indikerer et sammenhæng mellem informationsstyring og effektiviteten af den pågældende organisation. Dette fører til den antagelse, at bedre information i sidste ende vil føre til et bedre resultat af byggeprojektet. Selvom problemer i designinformation opleves jævnligt af entreprenører, accepteres disse som en betingelse for at drive forretning. Samtidig med at bedre designinformation er endnu ikke defineret for byggebranchen.
Building Information Modeling har det immanente løfte om at forbedre kvaliteten af designinformation ved at foreslå teknologier og metoder, som formodes at forbedre designinformationen. Men Building Information Modeling giver ingen mulighed for at måle disse forbedringer af design information.
Denne forskning introducerer designinformationskvalitet som ækvivalent til informationskvalitet inden for informationssystemer. Designinformationskvalitet er defineret som overensstemmelse af designinformationer leveret af designteamet til entreprenørens specifikationer for at kunne planlægge og udføre et byggeprojekt.
For at beskrive designinformationskvalitet otte kriterier er identificeret. Disse er:

- **Relevans –** omfang, rækkefølge og tidsramme for informationernes levering
- **Konsistens –** koordinering af designinformation, med hensyn til geometri, funktionelle krav og overholdelse af reglerne med standarder og forskrifter.
- **Korrekthed –** omfanget af manglende, forkert eller forældet design oplysninger.
- **Præcision –** nøjagtig geometri og entydige krav til byggeprojektets omfang.
- **Tilgængelighed –** indsats for at få sikker adgang til aktuel designinformation.
- **Distribution –** indsatsen for at håndtere, dele og fordele design oplysninger.
- **Fleksibilitet –** indsatsen for at omdanne, udtrække eller opdatere oplysninger til arbejdsopgaver.
- **Mængden af information –** antallet af dokumenter og filer, og andre medier, bør være hensigtsmæssigt for byggeprojektets omfang.

Kriterierne blev identificeret ved empiriske studier og teori om informationskvalitet i byggebranchen og andre industrier. Empiriske undersøgelser, blev udført for at forstå designinformationsproblemer, som entreprenøren (informationsmodtager) oplever. Disse problemer blev identificeret ved observationer og interviews foretaget i 12 organisationer.
En forudsætning for at forbedre designinformationskvalitet er evnen til at identificere og specificere informationskrav til opgaven ved hånden. Kun hvis krav er klare kan disse opfyldes. Informationskrav er opgaveafhængige, og i byggebranchen er de ofte også afhængige af projektet, person og tid i projektet. Dette skyldes at byggeprojekter opfattes som unikke, derfor er arbejdsflow og dermed informationsstrømmen også unik.
Videre hen foreslås i denne afhandling en metode til at identificere informationskrav i fællesskab mellem design- og udførelsesholdet. Metoden er baseret på *pull planlægning* fra lean construction. Desuden foreslås at anvende Information Delivery Manuals som dokumentation af informationskravene.

Udover at identificere disse kriterier, beskriver afhandlingen også observerbare fænomener, til at gøre hvert kriterium målbar. En skala for at score hvert kriterier baseret på den nuværende praksis foreslås. Skalaen består af fem punkter fra den traditionelle til den mest innovative praksis. Da teknologi og praksis ændrer sig hurtigt skal definitionen af hvert fænomen justeres regelmæssigt.
Endelig anvendes *designinformationskvalitetsrammen* på et byggeprojekt med henblik på at vurdere dets praktiske anvendelse. Rammen viser sig at give meningsfulde mål af forbedring af designinformationskvaliteten i projektet, og det peger også på områder med lav designinformationskvalitet for yderligere forbedring og efterforskning.
Designinformationskvalitetsrammen er naturligvis nødt til at modnes gennem sin anvendelse i forskning og praksis. Rammen giver midlerne i entreprenøren til at formulere problemer i designinformationskvalitet og gør dermed i sidste ende designinformationskvaliteten til et konkurrenceområde. Det giver entreprenøren også muligheden for at måle effekten af teknologi og procesforbedringer, som formodes at påvirke designinformationskvaliteten. Praksis kan også bruge denne ramme til at vurdere risikoen ved lav informationskvalitet. Forskning kan bruge rammen til at identificere forholdet mellem designinformationskvalitet og positive eller negative resultater f.eks. med hensyn til byggeskader, forsinkelser og budgetoverskridelser. Dermed kan det eftervises om BIM adresserer de nævnte problemer.

0. Structure of the Thesis

The structure of the thesis is divided into four parts and six papers. The four parts introduce the practical and theoretical point of departure, account for the research design, summarize the papers, and are finalize by conclusions on the entire PhD project. The research tasks that illuminate the research question are described in detail in the individual papers. Together, the parts and the papers they constitute the PhD thesis. The overall structure is as follows:

0.1 Part I – Practical Point of Departure

The first section introduces the topic by describing the problem observed by practice and the context of this problem in industry moving towards integrated practices and BIM. This is substantiated by an exploratory research of the use of BIM in practice. The section defines the research scope, which leads to the study of literature in the next part, the theoretical point of departure.

0.2 Part II – Theoretical Point of Departure

Part I described the relevance of the thesis to practice, and Part II places the thesis in the context of the body of knowledge. Apart from discussing the literature on BIM and design management, Part II relates research in BIM to the body of knowledge on information systems. This is done not only to draw on the findings of information systems field of research, but also in the pursuit of a research paradigm. The search for an ontological, epistemological, and – not least – methodological guidance has been an important part of the learning in this PhD project. Thus, the paradigm of design science within information systems has informed this work with respect to ontology, epistemology, and methodology. The final section introduces the social construction of technology, which has also informed the considerations of this thesis about the influences of the social and technological sphere the output of this research.

0.3 Part III – Research Design

The research design draws on the study's practical and theoretical point of departure in order to identify the knowledge gap that can be filled by research to contribute to the base of knowledge. This gap leads to research questions that are illuminated by research tasks. Furthermore, Part III accounts for the knowledge base on the research and identifies criteria of research quality for this research. As a courtesy to the reader and to highlight the connection between the papers that constitute the other part of this PhD thesis, the papers are summarized and related to each other.

0.4 Part IV – Implications and Conclusion

The final part summarizes how the research questions have been addressed. The relation to practice is of great inherent importance to this research; therefore, the usefulness of the results is discussed. The claimed contribution to the base of knowledge is stated and the predicted impact on practice is described. Part IV also suggests further research in the field and provides some concluding remarks.

0.5 Part V – The Papers

The papers that comprise this thesis can be seen in the list of papers. Each paper represents an independent part to inform the research question, and is publishable at a research conference or in a peer-reviewed journal. The papers are attached to the thesis.

Part I – Practical Point of Departure

This part accounts for the practical point of departure. It discusses the motivational problem, the influence of new forms of project delivery and BIM on the architectural, engineering and construction industry, and an industry perspective on BIM. These points lead to the identification of this research scope, which later informs the research questions, at the end of this part.

1. Introduction

The information we [as contractors] *receive from the designers is not good enough for our use. This is a contractual problem. Designers are not paid to deliver good information; they are paid to deliver the industry's standard quality, which is insufficient and uncoordinated design information.*

[Senior Project Manager]

The above quote indicates that insufficient design information is the *industry standard*, at least in the Danish architectural, engineering, and construction (AEC) industry. Briefly, design information is all the information, such as drawings, specification and 3D models, as well as emails, meeting minutes, answers to requests for information, and change orders, that communicate the design to the contractor for planning and execution of construction. Thus, the opening quote suggests that design information should be coordinated – that is, the drawings and specifications should not contradict each other – and should contain sufficient information at the right time for the contractor to plan and execute construction work. This point is one of the premises of this thesis.

This thesis is an industrially focused PhD project and it is part of the Danish industrial PhD program, in which the student is employed by a host company (in this case, MT Højgaard) at the same time as being enrolled at a university (in this case, the Technical University of Denmark). Industrial PhD projects are typically initiated based on a problem or challenge experienced by practitioners or a business opportunity. Consequently, the project has an apparent observed problem that motivates the research. The observed problem is substantiated in the following section by observations of the author, and will show that the design informational problem in construction companies is multi-faceted and needs further research.

Thuesen (2007) described this problem of receiving the necessary information as a vicious circle; the design team is under constant pressure to deliver drawings, while the construction team has to take flaws in the design into consideration. Kumaraswamy and Chan (1998) conducted a study on the causes of delays in delivering the construction work. They identified *delays in design information* and *long waiting time for approval of drawings* as the two most important reasons for overall delays expressed by contractors. In the same study, designers reported *unforeseen ground conditions* and *inadequate contractor experience* as the major causes of delays. The findings of Kumaraswamy and Chan can be interpreted as an indicator of Thuesen's vicious circle. That is, the designers are not able to deliver adequate drawings, due either to a lack of time or knowledge about what is needed. Thus, the information delivered by the design team is not good enough. Consequently, contractors base their planning and execution of construction on false assumptions and ask for more drawings. However, Kumaraswamy and Chan's findings could also indicate that designers and contractors are blaming each other for the delays, and that design information becomes a means by which contractors shift responsibility for delays to the designers.

The next section unravels the observed problems to clarify some of the different aspects of the design informational problems that the contractors face when planning and executing construction work. The observations of handling of design information increase the likelihood that an informational problem exists, rather than being created by contractors blaming designers. The opening quote of this section suggests that design information should be coordinated and sufficient. The description of the observed problems will show that the criteria for quality of design information must go beyond just these two criteria. New project delivery processes and the emergence of Building Information Modeling (BIM) in the AEC industry have an influence on the observed problems. Project delivery and BIM methods also provide a practical context for the research and are described herein. The observed problem and its context are the practical point of departure and the basis for defining the research scope. The practical point of departure leads to the theoretical point of departure; that is, the literature that informs this thesis. Part II discusses the theoretical point of departure. The research scope and theoretical point of departure will direct the research question and research method discussed in Part III of this thesis.

2. Observed Problems

This section describes the observed problem that motivated the research and elaborates the design informational problems in the AEC industry. The first observation is related to the author's office space at the host company and the second is related to a construction project. Both observations guide the direction of design information problems and design information quality, which is discussed later in this thesis.

2.1 In the Office Space

During his first two years at MT Hojgaard, the author shared an office space with an experienced contract manager named Knud[2]. During that time, Knud worked on several tender projects. Knud was very open-minded and not at all resistant to changes in technology and work methods. He had an iPhone, which he also used to view BIM models. Together, Knud and the author made visualizations of the schedule and construction site for Knud's tender projects. This impressed Knud and he used the visualizations to discuss the schedule, construction site layout, and production methods with his subcontractors and to assure the client that logistical challenges are handled.

Figure 2-1: View from the author's office (photograph by author).

The picture shown in Figure 2-1 was taken early on in the PhD project. The volume of the information – particularly the large number of binders – is worthy of note. Like most of his co-workers, Knud printed every email, drawing, specification, meeting minute; everything he received digitally. In this way, he even archived information that, by default, was digital as paper. The binders shown in the photograph only represent Knud's projects from the last three or four years. This is not because Knud never throws anything away, however, as the following conversation suggests:

[2] Name changed by the author.

> Contract manager: "Ole, do you remember the residential project I worked on?"
> Author: "Yes"
> Contract manager: "I wish I hadn't thrown all the binders out!"
> Author: "Why is that?"
> Contract manager: "Suddenly the client is interested in us again!"

Printed design information consumed a lot of paper and it can be difficult to find and extract information from large piles of paper for other purposes. This aspect of the informational problem is evident in most construction site offices. It could be argued that the format of the information does not matter as long as it comes from a coordinated, updated, central data repository, such as a BIM model. Still, if this output does not reflect the information requirements of the information consumer (that is, the contractor), the consumer must invest time and effort to extract the information needed to perform his work task.

Taking quantities is an example of how a paper drawing can be correct, but does not support the task. A drawing created from a BIM model shows the exact number and position of the doors. However, if the contractor only receives paper drawings, he must count the windows manually. The problem is not only the time consumed, but also the risk in miscounting, which is increased given that information about the doors will available in multiple documents, as will be shown in the following.

2.2 On a Construction Project

The following observations were made on the construction of a head office in the Copenhagen area with a design-build contract. The design information was archived both on paper and digitally. In total, 3268 design drawings have been issued within the design and construction period of 3.5 years.

2.2.1 Identifying Products

The task that was observed was the review of design information to identify the products and characteristics that constitute a curtain wall for procurement. The observations were documented by the author (see Figure 2-2) in business process modeling notation (BPMN) (White and Miers 2008). The purpose of the observation was to identify the design informational problems encountered during a task performed by practitioners on a regular basis. This design information described a sloped curtain wall (142 meters long, 3.5 meters high, and consisting of 108 windows) that supports the elevated roof of the atrium.

This task was performed by a project engineer who had to open 20 documents in order to find all the available information. The entire process took an hour and only half of these documents contained relevant information. The process has to be repeated frequently during design, planning, and construction and involved several people (including the project manager, design manager, estimator, planner, project engineer) and several tasks (such as estimation, procurement, schedules, and work plans). Therefore, a significant amount of time is spent obtaining information. The task is repeated, at least partially, for each revision of the drawings and documents related to the product; this case involved eight revisions.

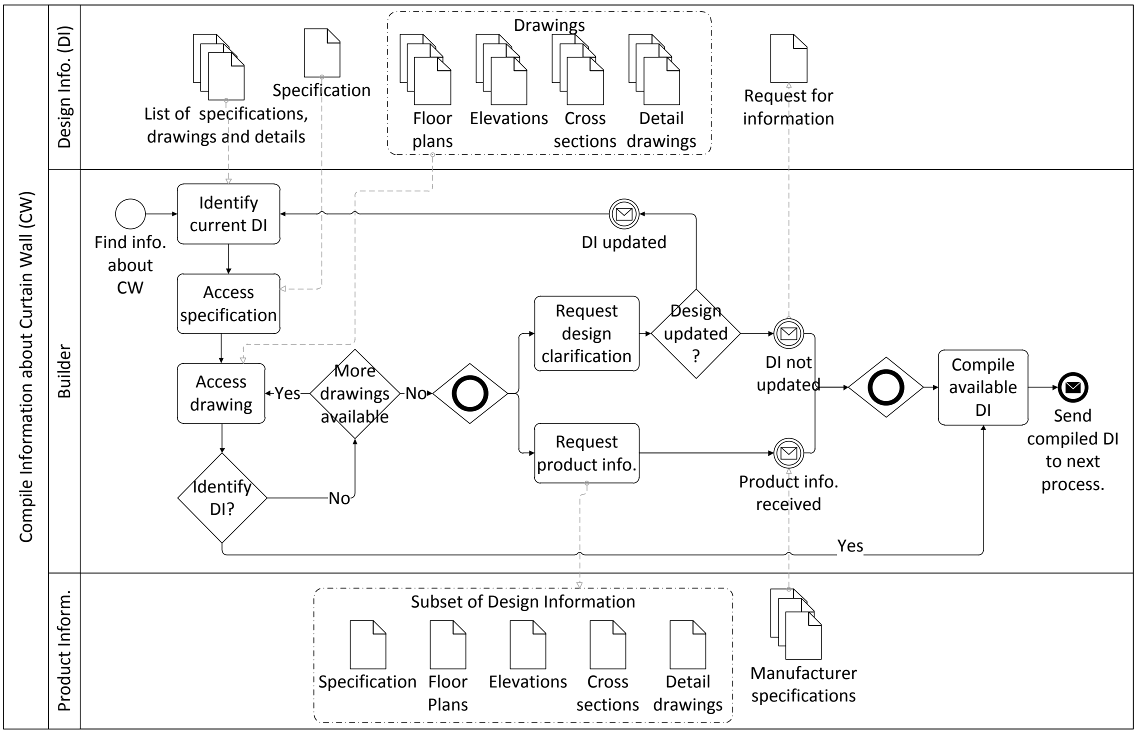

Figure 2-2. BPMN flowchart of observations made by the author during review of design information made on a curtain wall.

2.2.2 Description of the Observations

Figure 2-2 represents the observations made and the following is a description of the observation. First, up-to-date documents are identified on the project web site. Then the architectural specification is reviewed because it also contains references to drawings. Having accessed the drawings referenced in the specification, the project engineer surveys the list of drawings to find more relevant drawings because not all drawings are referenced in the specifications or in other drawings. If no more relevant drawings are available and the identified information is still insufficient or ambiguous, it is necessary to confer with either the designer or the building product manufacturer. In order to clarify information about a product, it is often sufficient to use the manufacturer's website or speak with a sales representative. Requesting information from the designer is a formal process, known as a request for information (RFI), which potentially results in an update of the design information. Obtaining an RFI answer from a designer often takes a week or more, depending on the question.

2.2.3 Problems Identified During the Observation

During the observed task, several problems were identified. First, if the design information requires clarification, the timing of the designer's or manufacturer's answer can interfere with the contractor's work flow. The process of finding the desired information is time-consuming because the structure of the design information was not appropriate for the task. Design information is structured around areas (that is, plans) and views (that is, elevations) that support the way in which designers work, rather than around products, which would support the way in which contractors work. The area-based information structure involves having information about one product in many documents.

The design information in the case described included three basic types of information:

1. **Explicit information** is apparent and unambiguous. This includes measurements, building products, color, surface covering, and materials requirements.
2. **Inferred information** must be calculated, measured, counted or inferred, or derived from the design information. A piece of information is transformed and becomes suitable for a certain purpose. Examples include quantities, elevations, some dimensions, and opening direction.
3. **Implicit information** refers to using product requirements instead of functional requirements. The actual requirement is then implicit in the product type; for example, instead of requiring sun shading, a product that provides sun shading is required. Implicit information adds ambiguity. For example, it is uncertain whether sun shading is a requirement or the product was chosen by mistake.

Furthermore, necessary information was missing or difficult to derive. The placement of the glass façade according to the module grid was not provided, and neither was the angle of the sloped façade; the angle had to be derived by the Pythagorean Theorem. Product data was outdated; two products in the specification no longer existed or had a changed name. Information was scattered across multiple documents and a product name that had not been mentioned before appeared on a detail drawing.

2.2.4 Summary

These observations revealed a list of problems with design information that was encountered by a professional, including time spent on finding and extracting relevant information, the timing of the information delivery, and the fact that the information structure and information can be implicit, ambiguous, missing, outdated, or even scattered over many documents. The list of informational problems indicates that information problems have multiple aspects that must be understood in order for them to be addressed. Part III of this thesis investigates these issues more thoroughly.

3. Project Delivery in the AEC industry

In the AEC industry, project delivery has traditionally been described as a phase-gate process. The process is divided into phases (such as schematic design, design development, and construction documents for the design process). At the end of each phase is a gate, at which point a decision is made regarding whether to go on based on the available information. The Stanford Project Heartbeat (Stanford 2010) is a textbook example of how the AEC industry applies the phase-gate model (see Figure 3-1). The Project Heartbeat has very clear informational deliveries defined for each phase and gate. Another example is the MT Hojgaard project delivery process for design-build (see Figure 3-2), which also defines phases and informational deliveries.

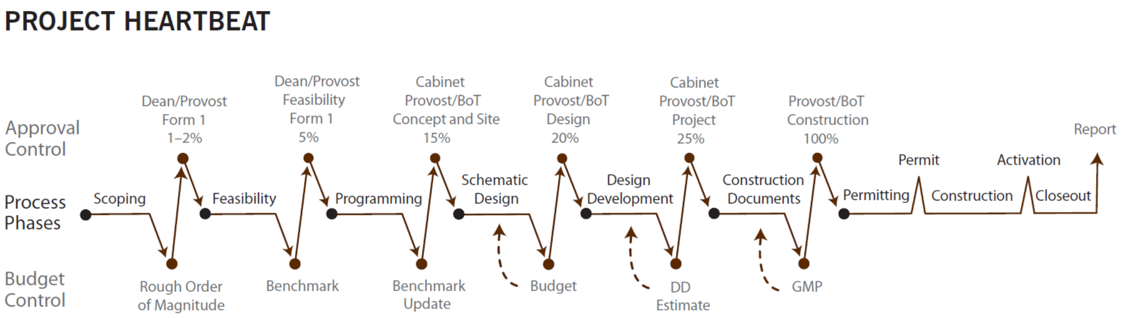

Figure 3-1: The Stanford Project Heartbeat for project delivery (Stanford 2010).

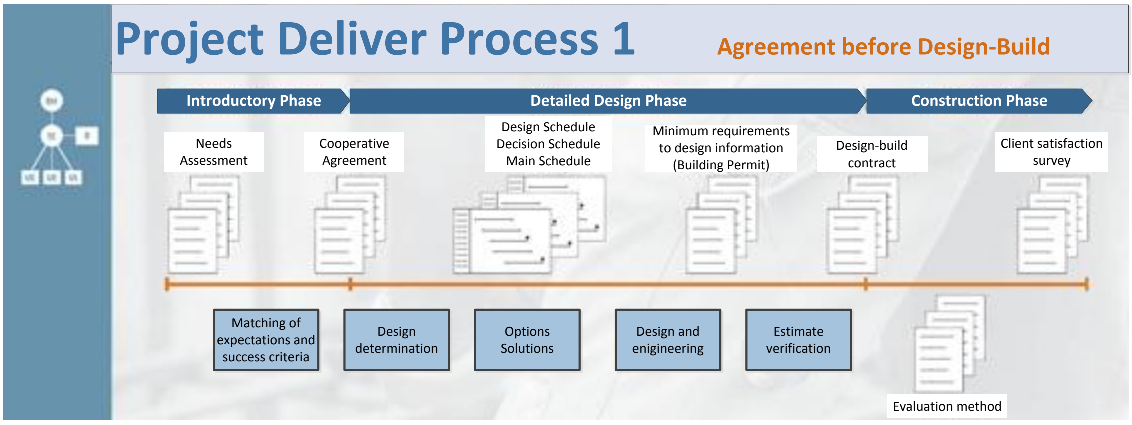

Figure 3-2: MT Hojgaard project delivery process in design-build (courtesy MT Hojgaard, translated by author).

The phase-gate model is generally accepted as a model of project delivery in the AEC industry and many actors have accommodated it to their process and apply it with more or less detail on the expected deliveries. The phase-gate model is sequential, which means that the output of the subsequent phase is the input for the next. Sequential process models like this are sometimes referred to as waterfall models because information can only flow downstream from actors involved in the earlier phases to the actors involved in the later phases.
However, new project delivery models are emerging. Information needs to flow both upstream and downstream because decisions and knowledge from actors in the later phases can influ-

ence the decisions in the early phases. One example is integrated project delivery (IPD), which the American Institute of Architects (AIA) has defined as:

> *A project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively harnesses the talents and insights of all project participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction.*
>
> (AIA 2007)

IPD is based on three principles: a *multiparty agreement* with primary roles of the project, such as an owner, an architect, engineers, general contractor and key subcontractors; *shared risk and reward* to encourage team work; and *early involvement of all parties* (Kent and Becerik-Gerber 2010). Hence, IPD acknowledges that more actors than the traditional design team possess knowledge that is important for the design of construction work. Consequently, constructors (contractors) and trade constructors (subcontractors) are involved from an early stage (see Figure 3-3). Therefore, tasks that are traditionally performed later in the course of design and planning construction, such as procurement, work planning and estimation, become parallel tasks with the design. Consequently, the traditional gates are minimized and communication occurs continuously. Pure IPD is still seldom seen, although similar effects are seen in other project delivery methods.

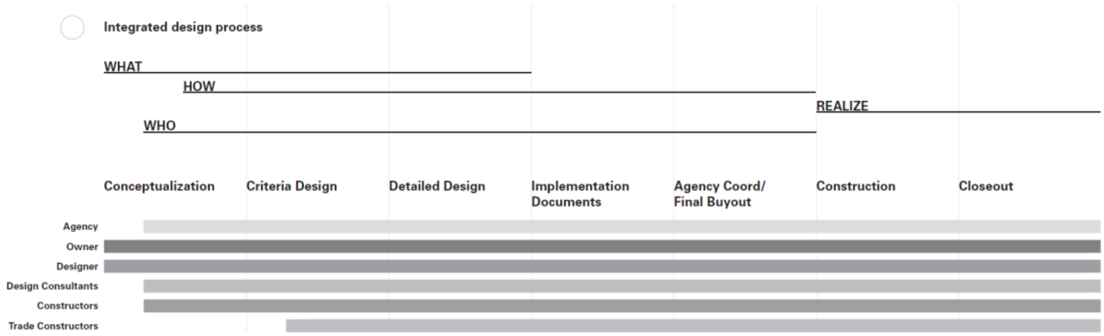

Figure 3-3: Integrated Project Delivery Process (AIA 2007).

An integrated process of project delivery also has requirements regarding the communication of design information, because information is delivered continuously instead of at the end of phases. This is why Building Information Modeling (BIM) and IPD are strongly tied. The U.S. General Service Administration defines BIM as follows:

> *Building Information Modeling is the development and use of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility.*
>
> (GSA 2007)

BIM is commonly depicted as the BIM cycle (see Figure 3-4 for examples), which shows the building model in the center and the project delivery process or different stakeholders forming a circle around it. The basic notion is that stakeholders retrieve the information needed for their tasks from the central information repository and leave the information of the construction they created. Although the central data repository is straightforward and seems logical and simple, it is challenging to implement. First of all, the information needs to be placed in the building model before it can be used by other project participants. Preferably, the information is placed before the next participant needs it, which helps achieve a continuous workflow. Accordingly, this requires prior agreement. The model progression specification (MPS) (AIA 2008) by the AIA and the information delivery manual (IDM) (ISO 2010a) are attempts to address this. The MPS and IDM are further discussed in Sections 8.4.1 and 8.4.2, respectively. It is presumed that the user will not only have requirements regarding the content of the information, but also how it is delivered (for example, as a digital building model). This issue and the solutions are further developed in Part III.

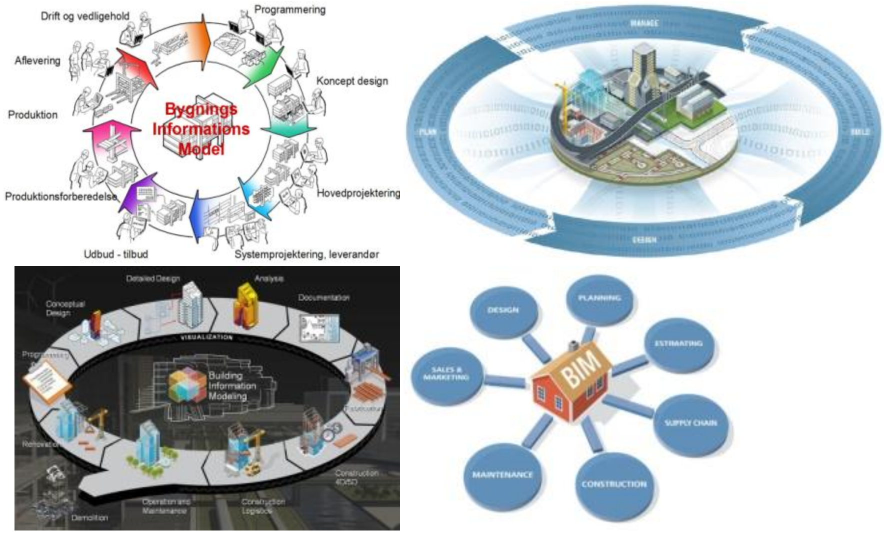

Figure 3-4: Example of the BIM cycle by the BIM group of Technical University of Denmark[3] (top left), Autodesk[4] (top right), Unknown[5] (bottom left) and Skanska[6] (bottom right).

[3] Technical University of Denmark, http://www.bim.byg.dtu.dk/BIMlab/Hvad-er-BIM.aspx, accessed 12-04-2012.

[4] Autodesk, http://images.autodesk.com/adsk/files/2011_realizing_bim_final.pdf, accessed 12-04-2012.

[5] Unknown, http://buildipedia.com/in-studio/design-technology/the-daily-life-of-building-information-modeling-bim, accessed 12-04-2012.

[6] Skanska, http://www.skanska.co.uk/Services/Design/Specialist-skills/Building-Information-Modelling-BIM/, accessed 12-04-2012.

4. State of the Art – An Investigation of Building Information Modeling[7]

This section summarizes the findings of a working paper that investigated the use and meaning of BIM in practice. This is one of the papers that comprises and is attached to the thesis. The State of the Art paper is discussed in this section because it reports on an exploratory research that has inspired the research scope of this paper. The title “State of the Art” refers to the fact that the paper supplements the traditional literature study in the beginning of a PhD project by an interview study of the use of BIM in practice to obtain a 2010 industry perspective to inform the subsequent research.

The focus of the study was to explain how BIM is used in the AEC industry and for which purposes. The method was open interviews with people who have experience working with BIM. The motivational question for this study is: *Why are people and organizations using BIM, and how are they using it?* The study was highly exploratory, which meant that it was not informed by theory, except in the method. The study draws entirely on the experiences, stances, and opinions of the interviewees. The research informs the body of knowledge with the practitioners’ perspective and application of BIM. The environment, in the form of the host company, benefited from insights into the practices of other companies.

The sample was architectural, engineering and contracting companies in selected countries. In total, 34 exploratory interviews were conducted with 47 individuals (see Table 4-1).

	Denmark	Finland	Germany	Sweden	UK	USA	Total
Architect	3	1	1	1	1	2	**9**
Engineer	4	2	3	1	2	0	**12**
Contractor	1	2	3	0	2	5	**13**
Sum	**8**	**5**	**7**	**2**	**5**	**7**	**34**

Table 4-1: Number of interviews by profession and by country.

The paper discusses several aspects and applications of BIM from the perspective of practitioners. Among the topics practitioners engage in are the struggle regarding who builds and maintains the building model, different BIM uses in contractors, the importance of life-cycle costs in the BIM investment considerations, as well as potential benefits, challenges, and means of measuring the benefits. However, three topics have primarily informed this research.

First, the paper identifies three uses of the abbreviation BIM in practice: building information model, building information modeling, and building information management. The notion of building information management is that IT can help organize and distribute the information. The information management perspective has confirmed that it is relevant to address the topic of improving design information.

Second, some practitioners see close collaboration as a prerequisite for using BIM. Others have observed that BIM also works internally in one company. However, there is general agreement that BIM supports closer collaboration and is supported by integrated forms of agreement, as

[7] Not published: Ole Berard (2012), State of the Art – An Investigation of Building Information Modeling, Working Paper.

design-build and IPD. BIM encourages synchronizing workflows and information exchanges, by making agreements on the information delivery.

Third, a model is created for a purpose and it is difficult to use it for anything other than its original purpose. Digital building models are often created to produce drawings and coordinate design solutions, and practitioners struggle later in the project when they seek to apply for other purposes such as quantity take-off and scheduling. This makes it necessary to explicitly identify possible applications early in the project. Contracts can prevent identifying later applications, which means that contractors sometimes remodel the project even if its design models exist.

This paper has emphasized the importance of managing information in design, planning, and execution of construction work. The purpose of information management is to make the right information available at the right time for the right individual in a setting that enables the individual to engage in a discussion of his or her informational needs.

5. Research Scope

The question remains as to whether better design information will lead to buildings being delivered on time, on budget, and with zero defects. It is at least plausible that better information management leads to greater efficiency and better output in the AEC industry, since it is reported by research in other fields (Banker et al. 2006, Alter 2008, Mithas et al. 2011). In the AEC industry, research indicates a relation between the quality of design information and building defects (Josephson and Hammarlund 1999), budget overruns (Reichelt and Lyneis 1999), and schedule delays (Sullivan and Harris 1986). Establishing the relation between design information quality and better outcome is not the scope of this research. However, this relationship is implicit in the notion of BIM and constitutes the basic assumption of this research; better design information enables the contractor to better plan and execute construction work. However, having defined design information quality, the output of this research can potentially establish the relationship by providing the means with which to measure design information quality.

Design information quality is a point of conflict between the design team and the contractor. Consequently, design information is of interest to practice. This interest is independent of whether it is – as described by Thuesen (2007) – a vicious cycle whereby contractors demand drawings and designer release unfinished material, insufficient drawings are used to justify delays, or the quality of design information is an actual problem.

The problem observed in practice indicates that contractors have several issues with the design information in the traditional process. More integrated forms of project delivery are supposed to address these issues. However, these new forms of agreement also require improved exchange and flow of design information; information exchange no longer occurs at the end of phases; instead, information exchange becomes continuous. The notion of BIM has the inherent promise of supporting the information exchange; therefore, it is a system for managing information – an information system. To provide a continuous and effective information flow, however, the requirements to design information and design information quality have to become explicit. Only when the requirements are known can they be assured of being fulfilled. Practitioners do experience that BIM models have to be built for a purpose; if they are not built for the intended purpose, it is difficult to adjust them. The need for a defined purpose increases the need for explicit information requirements.

Consequently, the scope of this research is the requirements contractors have regarding the quality of design information that enables them to plan and execute construction work. Requirements concern both the content of the design information and also accessing and working with the design information. This is seen in the context of an industry that moves into a more integrated practice, which is supported by information systems such as BIM.

Part II – Theoretical Point of Departure

This part accounts for the theoretical point of departure. Literature from BIM, Design Management, Information Systems and Socio Technical Studies will be discussed to identify the research questions, to inform the epistemological, ontological and methodological choices and to inform the findings of this research with knowledge from other fields.

6. Theoretical Point of Departure

The previous section identified the observed problem and research scope; these provide the underlying basis for the theoretical point of departure. The observed problem indicated that design information can be uncoordinated and insufficient, and contractors encounter problems with the time spent on finding and extracting relevant information. The timing of the information delivery can be problematic and the content can be implicit, ambiguous, missing, outdated, and even scattered across numerous documents. The research scope is the contractors' requirements for content, access, and ease of handling design information. Based on the observations, this part has determined the following fields of knowledge that inform research problem and scope.

- Managing the design information on a construction project is an important task of the contractor's design management. Design management will be discussed from the perspective of information management.
- BIM is well-established in research and emerging in practice, and improves the available information. Literature on BIM will be reviewed from the perspective of improving information flow.
- BIM manages information and becomes an information system. Theory and methodology of information systems have been studied in many fields. The notion of information quality is also of interest to this research.
- Research will be conducted on technology and organization. Constructivist approaches to technology, such as Social Construction of Technology (SCOT), are introduced to inform ontological, epistemological, and methodological choice and constitute a frame for analysis.

Therefore, this part presents theoretical points of departure: design management, BIM, research in information systems and SCOT. These will help identify the gap in existing knowledge that this study has sought to inform. The theoretical points of departure will not only lead to the relevant research questions, but will also inform the choice of research method and tasks to address the research question. This section discusses the relevant parts of the fields of knowledge in detail. The essence of these discussions inevitable informs the papers published on the research tasks (cf., List of Papers Appended). This part discusses the points of departure, while the gap in knowledge, research questions, research methods, and papers are introduced in Part III.

7. Design Management as Information Management

Ralph and Wand (2009) defined design as:

> *Design (noun) is a specification of an object, manifested by an agent, intended to accomplish goals, in a particular environment, using a set of primitive components, satisfying a set of requirements, subject to constraints*.
>
> (Ralph and Wand 2009).

The definition of the verb *to design* draws on the definition of the noun and is formulated as: “to create a design, in an environment (where the designer operates)” (Ralph and Wand 2009). Although Ralph and Wand defined design in general, their definition can also be applied to building design. When designing a facility (that is, the object), the primary agents are designers, such as architects and engineers. Integrated practice (cf. section 3) encourages the involvement of other actors, such as contractors, building product manufacturers, and subcontractors. Managing design and the design process has many different aspects; Ralph and Wand (2009) identified five different views on design, based on literature: problem solving, problem finding, a learning process (epistemic), a result of inspiration and growing an idea. Design management is also about managing people, innovation and creativity, functionality, requirements, and constraints. All of these different views on design benefit from management. Another important part of design is the information to communicate the design. This section describes design management from the perspective of managing information to achieve information flow. It draws on literature of lean thinking and design of construction work. The theoretical background of lean design is discussed first, and then techniques for achieving design flow accordingly are described.

7.1 Views on Design

Koskela (2007) described three views on design: design as transformation, flow, and value generation. All three are appropriate for describing design; transformation focuses on the individual design discipline, flow focuses on the interaction between parties involved in the design, and value generation focuses on the final customer of the design (that is, the building owner). Flow and the interaction between designing actors is of most interest to this research. However, all three views are necessary to understand design and are introduced briefly below.

7.1.1 Design as Transformation

Information is an important element of design. Den Otter and Prins (2002) described design as: “processing, multidisciplinary, design information concurrently through different design organizations.” Their description of design emphasizes the importance of processing information. Koskela’s (2007) transformational concept is that work (that is, design activities) is conducted on an input (that is, requirements) in order to deliver an output (that is, design information). Design as transformation of information is generally accepted in practice and research. For design planning in the transformational view, the work breakdown structure is essential because it defines the scope of work by the individual tasks. Koskela had the following criticisms of the transformational concept:

- Sub-optimization: focus is on the efficiency of individual tasks.
- Problems in prevalent practice, such as slow product launch, poor quality, and inefficiency (Putnam 1985).

- Not all activities contribute to transformation (for example, information is inspected, stored, and communicated).
- Missing customer focus: neither the total process, nor parts of it, is related to customers.

(Koskela 2007)

Sub-optimization becomes a problem when the task efficiency counteracts system efficiency. According to Putnam (1985), many problems in design practice originate from design, manufacturing, and quality control departments only being linked at the points where a product moves from one department to the next (cf. the phase-gate model in Section 3). Consequently, the transformational concept is not sufficient to describe the design process because activities that do not contribute to transformation are also part of design.

7.1.2 Design as Flow

The transformational concept of design is one of the three concepts of design described by Koskela (2007). The second is design as flow. The importance of flow is implicit in den Otter and Prins' (2002) definition of design. It allows concurrent processing of information in multiple organizations. In the flow concept, a piece of information can be in one of four stages:

- Transformation
- Waiting
- Moving
- Inspection

(Koskela 2007)

Essentially, waiting, moving, and inspection are wasteful and unnecessary, and should be eliminated. Furthermore, the transformation stage consists of design and rework. Rework is also wasteful. If waste cannot be eliminated, it should be reduced. Hence, Koskela (2007) suggested that moving information be addressed by collocating design teams. Collocation encourages the oral transfer of information. Waiting on information can be addressed by reducing batch sizes and splitting design tasks. Information technology also has an important role in enabling information flow. Furthermore, Koskela's notion of pairing suppliers and customers is worth noting:

> *Design can also be conceived as pairs of supplier-customer. Poor specification of a supplier's work in relation to an internal customer's needs leads to added effort in the customer's activity, and also possibly to rework or continued work in the supplier's activity.*

(Koskela 2007)

Customers of designers can either be other designers (for example, a structural engineer needs the wall layout from the architect in order to identify the bearing walls) or contractors (for example, a ventilation subcontractor needs the air flow specification from the mechanical engineer in order to decide which products to procure). As the design of the designers and the planning of the contractor become parallel tasks (cf. Section 3), the focus on flow becomes increasingly important. The means to achieve flow are discussed in Section 7.2.

7.1.3 Design as Value Generation

Koskela's (2007) final concept is design as value generation: "Value is generated through fulfillment of customer needs and requirements." Koskela argued that requirements need to be identified, captured, and optimized. Identification of requirements needs "a rigorous needs and requirements analysis at the outset in close co-operation with the customer(s)." He suggested the quality function deployment method (Bahill and Chapman 1993) to communicate and prioritize client requirements. Optimization is necessary because one requirement can be fulfilled through many subsystems, and requirement fulfillments can counteract each other. Consequently, optimization is needed to identify the design that best conforms to the client's requirements. All three concepts of transformation, flow, and value generation are related. Koskela (2007) noted:

> *Each task in itself is a transformation. In addition, it is a stage in the total flow of design, where preceding tasks have an impact on it through timeliness, quality of output, etc., and it has an impact on subsequent tasks. Also, certain (external and internal) customer requirements direct the transformation of all input information into solutions in each task.*
> (Koskela 2007)

In other words: "Poor definition of needs (domain of value management) causes disruption to task and flow management through untimely design changes" (Koskela 2007). Koskela's primary concern was identifying the final customer's needs (that is, the owner and users of the construction work).

7.2 Achieving Flow in Design

Koskela (2007) discussed the supplier-customer relationship in which the design team and the contractor engage to achieve flow, which is a topic if this research. Tilley (2005) described the problem of informational flow in design management:

> *There is often insufficient consideration given to the information required from others to enable these tasks to actually be completed as and when required to minimize waste. By failing to plan the information flows in relation to the various tasks, delays in obtaining the information often occur, which can either lead to delays in completing design tasks, or having designs and design documents issued with missing information.*
> (Tilley 2005)

Consequently, the failure to identify information needs and to plan information flow results in lower quality of design information for the contractor. The challenge of design management is to plan the design process. Flow is established by identifying the ideal sequence of design tasks and providing needed information and decisions in time to maintain progress. The design structure matrix (Steward 1981) and the last planner system (Ballard 1999) provide techniques to plan the design process and achieve flow.

7.2.1 The Design Structure Matrix

The design structure matrix (DSM) method was first published by Steward (1981). Since then, it has been applied in design and engineering in many industries to model the design of complex systems to understand the relationship and interaction between components (Browning 2001). According to Browning, interactions that are modeled in the DSM can be spatial, energy, information and material. It is a useful tool for product developers, project planners, project managers, system engineers, and organizational designers.

The DSM is a square matrix, known as a N^2 diagram, in which both rows and columns contain the same list of tasks, components, or organizational units. Every element's relationship to the other tasks is marked (see Figure 7-1). The tasks can then be sorted so that there are no marks above the diagonal; this is the ideal sequence. The sorted matrix serves as input to a schedule. Tasks that depend on other tasks are sequential, while tasks without dependencies can be scheduled concurrently. Tasks with marks above the diagonal indicate interdependencies and are iterations (Koskela et al. 1997).

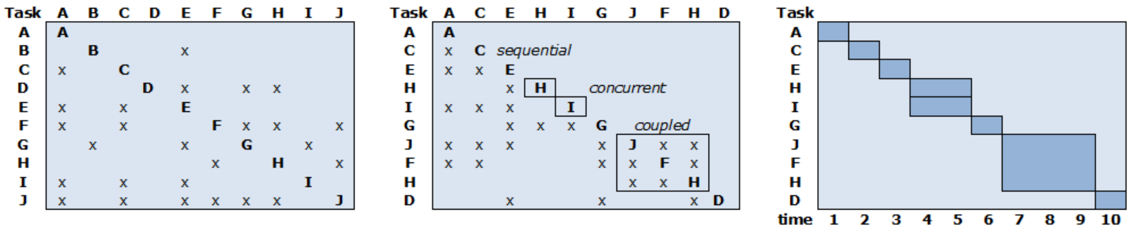

Figure 7-1: DSM, unsorted (left), sorted (middle) and scheduled (right) (adapted from Koskela et al. 1997**).**

In the AEC industry, the design structure matrix has been applied in research (Koskela et al. 1997, Choo et al. 2004, Austin et al. 1996, Lahdenperä and Tanhuanpää 2000). While research in the AEC is primarily in component- or activity-based DSM, Pektas and Pultar (2006) studied the application of parameter-based DSM (Browning 2001). Using an example of a suspended ceiling by relating all design parameters related to each other, Pektas and Pultar identified the number of parameters as a major challenge. Attempting to capture all parameters would be unrealistic; therefore, only the critical ones should be captured.

7.2.2 Design Phase Scheduling

In current practice, scheduling the design process is often based on drawing due date schedules (Koskela 2007, Pektas and Pultar 2006). Design packages are pushed at design reviews (for example, at phase gates) to the contractor, and subsequent information is pulled (Matti et al. 2005). During design, engineers create task-specific views of design information (that is, drawings) that accommodate their way of working (Haymaker et al. 2004). Drawings created this way eventually become part of the design information, under the assumption that a view needed to design a building is also needed to build it. Hence, the customer's (that is, the contractor) influence on design information layout, content and timing is limited. Prevalent design information is neither in layout and content, nor in delivery timing to support construction. Instead, it supports communication between designers.

Ballard (1999) suggested a variation of the last-planner system for use in design. This system is most commonly used for planning construction work (Ballard 2000). The last planner is the person who gives the actual work assignments to the construction workers (for example, foremen and supervisors in construction). The foremen plan what will be done in the near future on the basis of what can and should be done. This is also called looking ahead. The last-planner system is typically a pull system by planning backwards from the final task. Ballard and Howell (2003) describe the pull process of phase planning:

1. Define the work to be included in the phase; for example, foundations, building skin, etc.
2. Determine the completion date for the phase, plus any major interim releases from prior or subsequent phases.

3. Using team planning and sticky-backed cards on a wall to develop the network of activities required to complete the phase, working backwards from the completion date, and incorporating any interim milestones.
4. Apply durations to each activity, with no contingency or padding in the duration estimates.
5. Reexamine logic to try to shorten the duration.
6. Determine the earliest practical start date for the phase.
7. […]

(Ballard and Howell 2003)

Pull systems are known from planning and production control in lean manufacturing (Womack et al. 2007). An example is Kanban (Sugimori et al. 1977). In Kanban, the subsequent manufacturing process sends a signal to the preceding manufacturing process to send more parts. When parts are removed, new parts are produced. Pulling parts reduces overproduction, inventory, and work in progress, and visualizes the work flow. Continuous production and a constant need for new parts are conditions for Kanban in manufacturing (Krupp 1999, Deleersnyder et al. 1989).

Pull planning in software development is also referred to as Kanban (Ikonen et al. 2010). The technique is based on regular, cross-functional team meetings to classify work items in different phases of the project as ready, work in progress, and done. The purpose is to identify work that can be conducted, address conditions that prevent work from progressing, and limit work that in progress. These look-ahead meetings are conducted daily or weekly.

Construction operates on few similar batches, and constant production cannot be assumed. To apply pull-planning in construction, it is necessary to be certain that what is planned will be executed. This time span of certainty is called a *window of reliability*. In order for pull to work, the window of reliability must be greater than suppliers' lead time for a given component (Ballard 1999). Windows of reliability are typically short. Look-ahead meetings must be every two to five weeks.

Pull techniques can also be applied in design, which inherently operates in small batches. Ballard (1999) also proposed the activity-definition model (see Figure 7-2). The scheduled activity provides the output. For this output design criteria are specified or clarified. Consequently, resources need to be allocated. Finally the output is tested against criteria and either released or redone.

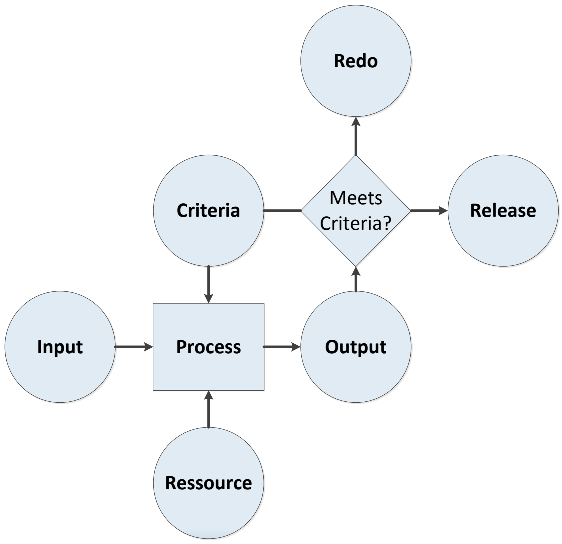

Figure 7-2: Activity definition model (Ballard 1999)

The users of the design output (that is, design information) are pulling it into their process. Ballard (1999) concluded:

> *Joint assignment of design tasks to both provider and puller both promotes common understanding of criteria and also ensures that resources are used first to do work that is needed now by someone else.*
>
> (Ballard 1999)

According to Ballard (2008), the benefits of pull scheduling are reduced overproduction and batch sizes, and greater concurrency of design tasks. Design pull-planning was used on a case study (Ballard 2002), the conclusion of which was that the transition to pull-planning was not completely fulfilled on the project and that unsound tasks were allowed into the look-ahead windows.

7.3 Summary

Information is an important element in building design. The literature of design management acknowledges informational problems (Tilley 2005). However, the nature of the informational problems has not been studied in detail. Design has traditionally been seen as the transformation of information. However, to counteract problems in design, such as slow product launch, poor quality, and inefficiency, other understandings of the design process are necessary.

The DSM and design-pull scheduling are suggested to address problems in achieving information flow. The DSM can be applied for varying purposes and details, but it provides the means to identify the interaction between different elements in the design process. Pull scheduling suggests a supplier-customer relationship between actors in design, planning, and execution of construction work over an informational product. The supplier-customer relationship helps establish information flow by specifying information needs. By applying both methods, information requirements can be identified and flow can be established. Identifying the necessary information and establishing flow of information is an important part of improving the contractor’s work. However, identifying information requirements addresses the observed problems partially, since it addresses what information is delivered when, but not necessarily how.

8. Building Information Modeling

The abbreviation BIM can refer to a building information model, the digital artifact, building information modeling, the process of creating and using a digital building model, or sometimes even building information management (buildingSMART 2012). Furthermore, there is no common agreement, either in research nor in practice, about what comprises BIM. This section introduces the present thesis' definition of BIM and area of interest within the field. BIM seeks to change the current medium of specifications and drawings for communicating design information during design, planning, and execution of construction work. The prevalent medium is very old, and the history of specifications and drawings as design information is introduced to show how deeply rooted these documents are in today's practice. The history of design information is compared to the vision of digitally integrating information, from which the notion of BIM originates. Finally, the means to model information flow from the BIM literature are introduced to inform the observed problem and scope of this thesis.

8.1 Definition and Delimitation

BIM's mission is to supplement, and eventually replace the traditional medium of design information (that is, documents) in the AEC industry with digital and integrated information, and to influence how buildings are design, planned, and executed. However, no agreement has yet been reached regarding the definition of BIM. Eastman (2009) described BIM on the Georgia Institute of Technology website as follows:

> *BIM involves representing a design as objects – vague and undefined, generic or product-specific, solid shapes or void-space-oriented (like the shape of a room), that carry their geometry, relations and attributes. The geometry may be 2D or 3D. The objects may be abstract and conceptual or construction detailed. Composed together these objects define a building model (not a BIM, in my view). If an object is changed or moved, it need only be acted on once. BIM design tools then allow for extracting different views from a building model for drawing production and other uses. These different views are automatically consistent – in the sense that the objects are all of a consistent size, location, specification – since each object instance is defined only once, just as in reality. Drawing consistency eliminates many errors.*
> *Modern BIM design tools go further. They define objects parametrically. That is, the objects are defined as parameters and relations to other objects, so that if a related object changes, this one will also. Parametric objects automatically re-build themselves according to the rules embedded in them. The rules may be simple, requiring a window to be wholly within a wall, and moving the window with the wall, or complex defining size ranges, and detailing, such as the physical connection between a steel beam and column.*
>
> (Eastman 2009)

For Eastman, BIM is the process of creating and maintaining a parametric, object-oriented, rule-based building model. BIM creates an information repository for the AEC industry. The closely related concept of virtual design and construction (VDC) goes beyond Eastman's definition of BIM. The Center for Integrated Facilities Engineering (CIFE) at Stanford University described VDC as:

The use of multi-disciplinary performance models of design-construction projects, including the Product (that is, facilities), Work Processes and Organization of the design–construction–operation team in order to support business objectives.

(CIFE 2012)

Thus, VDC uses the information repository for business purposes. Others have incorporated the creative process using the building model in their definition. BuildingSMART provided one example:[8]

Building Information Modelling: Is a BUSINESS PROCESS for generating and leveraging building data to design, construct and operate the building during its lifecycle. BIM allows all stakeholders to have access to the same information at the same time through interoperability between technology platforms.

(buildingSMART 2012)

VDC and BIM are closely related in meaning and scope. There are continuing discussions in academia and industry about which best describes the creation and use of digital and integrated information in design, planning, and execution of construction work. For the purposes of this thesis, BIM is defined as:

Building Information Modeling or BIM is the creation and use of information-bearing, object-oriented, geometrical models of a building utilized in design, planning, and execution of construction work.

Figure 8-1: Definition of BIM in this thesis.

Accordingly, BIM comprises both the creation and the use of the digital building model as an AEC project information repository to support various applications in designing, planning, and executing construction work. The definition is pragmatic and describes the use of BIM in this research. This definition also excludes aspects of BIM that are not relevant to this research, such as operation and facilities management. The purpose is not an exhaustive definition, but an operational clarification of BIM.

There is extensive research on how to create a digital building model and for what applications the building model can be used. The creation and use of building models by BIM is only of peripheral interest to the problem and research scope, and will not be discussed in detail. It is important that the information is present in the models.

It is tautological to state that information must be entered into the digital building model prior to it being used for design, planning, or execution of construction. However, information (both in content and level of detail) depends on the task to be solved (Eastman et al. 2010), and it is important to be aware that it can be a challenge to obtain timely information. The use of information from digital building models potentially creates new information that needs to be fed back to

[8] buildingSMART International is a neutral, international, non-profit organization supporting open BIM, with regional chapters in Europe, North America, Australia, Asia, and the Middle East (www.buildingsmart.com).

the model for next use. Information requirements are different for every kind of use of a building model, such as quantity take-off, scheduling, and structural analysis (see Figure 8-2). This retrieval and placement of information for specific tasks becomes a multifaceted network. This network is often simplistically depicted in the BIM cycle (cf., Figure 3-4 in Section 3) by an arrow between the building model and the actors, phase, or applications of the model.

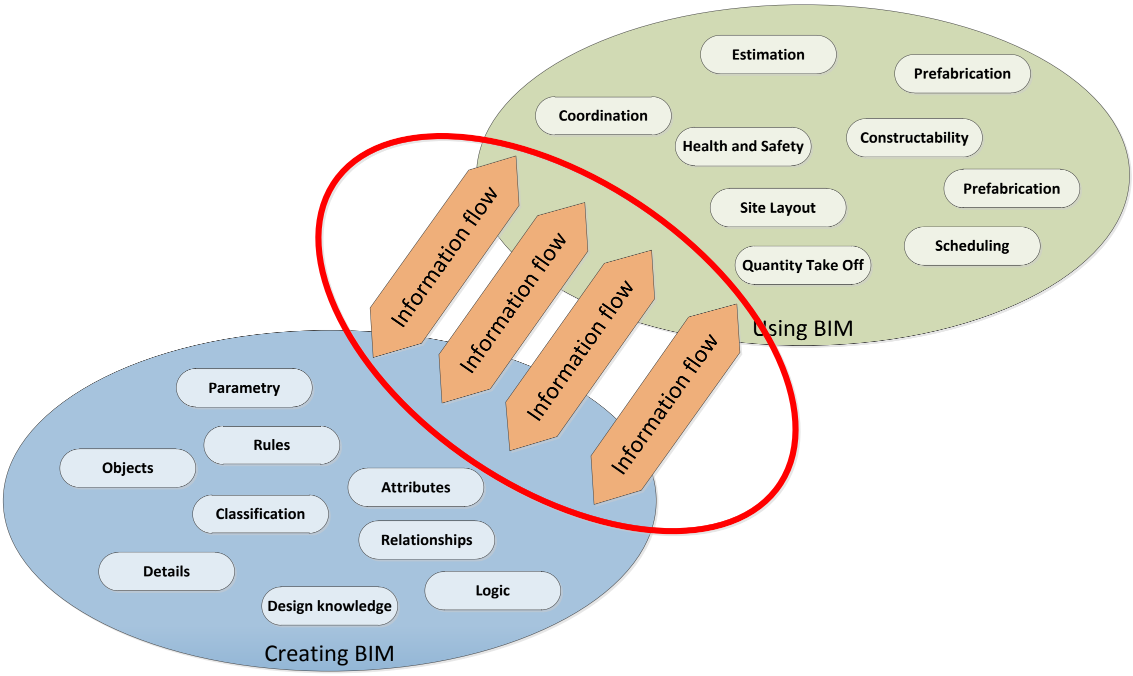

Figure 8-2: The scope of this section.

In order to establish information flow, task-specific information must be contained in the digital building model before it is needed. The building model must have the technological infrastructure to contain this information. This section discusses two approaches to establishing the information flow identified in BIM literature. The first is the technological vision of integrated information. This makes information available by providing an information infrastructure. The second approach is introduced by suggesting methods for providing relevant and timely information for the task at hand.

8.2 The History of Design Information

Architectural drawings, as they are known today, have been widespread since the Renaissance.[9] Their distribution is documented by a large body of drawings from the 16th century onward (Ackerman 1997), and also in artwork (see Figure 8-3 for an example of two men working on a drawing).

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[9] The concept of the Renaissance, which aimed to achieve the rebirth or re-creation of ancient Classical culture, originated in Florence in the early 15th century and spread throughout most of the Italian peninsula; by the end of the 16th century, the new style pervaded almost all of Europe, gradually replacing the Gothic style of the late Middle Ages. It encouraged a revival of naturalism, seen in Italian 15th-century painting and sculpture, and of Classical forms and ornament in architecture, such as the column, round arch, tunnel vault, and dome (Encyclopedia Britannica).

Figure 8-3: Tommaso Manzuoli detto Maso da San Friano: Doppio ritratto maschile, 1556.[10]

Many major construction projects took place in Medieval Europe, especially large cathedrals and churches in the Gothic architectural style[11] (12th to 16th centuries) (Prak 2008). The early Gothic building master was both an architect and a contractor, who communicated his design verbally and by sketches on the site (Toker 1985). Masonry fabrication was even communicated using scale wooden templates (Prak 2008). Gothic masters managed construction site through their presence.

In the second half of the Gothic age, the roles of the architect who designed the building were separated from the contractor who oversaw construction. Famous masters designed and built multiple buildings simultaneously and needed assistants to oversee the daily work. They needed documents to communicate the design. One of the earliest examples of these documents was the construction of the north half of the Palazzo Sansedoni in Siena, Italy (1340), studied by Toker (1985). A contract, consisting of orthogonal to-scale drawings (1:48) with horizontal and vertical measures, remains from the site. There were also specifications regarding what could be represented on the drawing (for example, toilets), references to church windows, and a client-designer contract specifying responsibilities, financial security and terms of design changes. Even though the level of detail was not comparable to modern shop drawings, Toker argued that it was sufficient for the contractor to transform the design into a building without the architect present. Since then, the roles of the architect and the contractor have grown apart. Even today, the design is communicated by drawings that are orthogonal, to scale, with measurements, and specifications.

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[10] Tommaso Manzuoli detto Maso da San Friano: Doppio ritratto maschile (Portrait of Two Men; here identified as Lorenzo and Zanobi Pagni), 1556. Oil on panel, 115 x 90 cm, Museo nazionale di Capodimonte, Naples, Italy.

[11] Gothic architecture: architectural style in Europe from the mid-12th to the 16th century, particularly a style of masonry building characterized by cavernous spaces with the expanse of walls broken up by overlaid tracery (Encyclopedia Britannica).

8.3 The Vision of Integrated Information

In the AEC industry, the emergence of personal computers and computer-aided design (CAD) in the 1980s fostered the vision to use of computers, databases, and applications for design, planning, and construction rather than drawings and specifications. Eastman (1981) described "integrated design databases" that connect geometry and product properties to enhance productivity and enable design, shop drawings, and cost estimates. As CAD became widely accepted in AEC, the geometry was stored in CAD files. The geometry could then be linked to object data in other databases and extracted by logical queries to perform "other [than drawing] functions" (Teicholz 1989).

The Industry Foundation Classes[12] (IFC; ISO/PAS 16739) (ISO 2010b) have been developed as a means to integrate CAD and BIM software products. They are extended and maintained by buildingSMART. Steel et al. (2012) noted that IFC has provided interoperability with relative success. However, the major challenges of the IFCs are inconsistent modeling styles (Steel et al. 2012). Integration of information has been a focus in IFC research. Development tools include the BSPro Com server for interoperability (Karola et al. 2002), as well as collaborative platforms such as the Design Information Management System (Lee et al. 2003), WISPER (Faraj et al. 2000), and a framework of a design information server (Chen et al. 2005) based on IFC.

Zamanian and Pittman (1999) argued that the AEC industry is diverse and fragmented, and also that AEC information evolves non-sequentially by an organizationally disjointed team. Consequently, they opposed the creation and deployment of any large, rigidly structured schema to satisfy all AEC disciplines. Instead, Zamanian and Pittman encouraged open-architecture software to facilitate collaboration and information sharing by means of several protocols used in a loosely coupled, multi-layered system. Each AEC project would likely adopt a different combination of these protocols to meet its specific needs.

Information has to be seen in the context of the task (Eastman et al. 2010), because work routines in the AEC industry change based on participants and projects. Even during the execution of projects (Hartmann et al. 2009), construction knowledge has not yet been sufficiently formalized (Fischer 2006). Therefore, task-specific information is unique for every project.

The above research focuses on developing the infrastructure of omniscient database by interconnecting different information sources. Other research accepts that information needs to be understood in the context of task, project, and actor, as acknowledged by Eastman et al. (2010). Boddy et al. (2007) envisioned developing construction projects and task-specific (for example, estimation, energy analysis, scheduling) scenarios that described information in the context of the work performed. It integrates both unstructured data from documents and structured information from databases through semantic analysis in the information repository.

[12] Industry Foundation Classes are a common data schema that makes it possible to hold and exchange data between different proprietary software applications. The data schema comprises information covering the many disciplines that contribute to a building throughout its lifecycle: from conception, through design, construction and operation, to refurbishment or demolition. Industry Foundation Classes, IFC, are the main buildingSMART data model standard. The IFC format is registered by ISO as ISO/PAS 16739 and is in the process of becoming an official International Standard ISO/IS 16739. buildingSMART, 2012, http://buildingsmart.com/standards/buildingsmart-standards/if.

8.4 Modeling Information Flow

Pull scheduling in design management (cf. Section 7.2.2) can provide a means to identify design information requirements in the context of task, project, and actor. Documentation of these requirements is only partially addressed by the design-structure matrix. Research and practice in BIM provides other methods to model and document information requirements and flow. Modeling information flow serves many purposes, among them as a legal agreement and optimization.

Notations for business process modeling provide the methods to model information flow. According to Curtis et al. (1992) notations for modeling, business processes for information systems can be described by four perspectives:

- **Functional** – represents what process elements are being performed, and what flows of informational entities (such as data, artifacts, products), are relevant to these process elements.
- **Behavioral** – represents when process elements are performed (such as sequencing), as well as how they are performed through feedback loops, iteration, complex decision making conditions, entry and exit criteria, and so forth.
- **Organizational** – represents where, and by whom (which agents) in the organization process elements are performed, the physical communication mechanisms used for transfer of entities, and the physical media and locations used for storing entities.
- **Informational** – represents the informational entities produced or manipulated by a process. These entities include data, artifacts, products (intermediate and end), and objects. This perspective includes both the structure of informational entities and the relationships among them.
  (Curtis et al. 1992)

List and Korherr (2006) conducted a review of seven business process modeling languages[13] according to Curtis et al.'s (1992) perspectives. List and Korherr concluded that all seven languages had shortcomings in the organizational and informational perspectives, whereas functional and behavioral perspectives are generally well implemented.

8.4.1 The Information Delivery Manual

The information delivery manual (IDM; ISO 29481-1; ISO 2010a) is developed and maintained by buildingSMART. The IDM compromises a collaborative method to identify business process and information requirements; it is also a notation to model processes and information flow that is specific for the AEC industry. The IDM extends the well-known business process modeling notation (BPMN) (White and Miers 2008). Other process modeling notations treat information as documents. IDM goes beyond documents by encouraging in-depth descriptions of information elements, such as objects and their attributes, and the exchange of information bearing objects through digital models. The focus on objects and attribute makes IDM native to BIM. The IDM comprises the following four elements (Karlshoej 2011b):

- **Process map** – to document the functional and behavioral perspective in BPMN.

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[13] These are UML 2.0 Activity Diagram (AD), Business Process Definition Metamodel (BPDM), Business Process-Modeling Notation (BPMN), Event Driven Process Chain (EPC), Integrated DEFinition Method 3 (IDEF3), Petri Net, and Role Activity Diagram (RAD).

- **Involved actors** – narratives describing the roles, for the organizational perspective.
- **Exchange requirements** – to describe the informational perspective.
- **Logical constraints** – business rules described by a narrative to elaborate the functional perspective
(Karlshoej 2011b)

In addition to the notation to document the flow of information and the needs of exchanged information to perform tasks, IDM comprises a technique to model and re-engineer a process. The IDM technique utilizes collaborative process re-engineering by involving multiple competencies (such as domain and software experts), as well as expertise on BIM and IDM, to re-engineer cross-functional processes.

The IDM is part of the information exchange framework for certifying IFC software (Wix and Karlshoej 2010). Other parts are model view definitions (MVD) (Hietanen 2006), which translate IDM into a document for software development, and Industry Foundation Classes (IFC; ISO/AWI 16739) (ISO 2010b), which provide the data structure. Although the three standards are closely affiliated, they are not inherently interconnected, neither by ISO 24981-1 or the US National BIM Standard (NBIMS) (NIBS 2007). Instead, the contribution of the IDM is beyond IFC certification. An IDM may even become a legal agreement (NIBS 2007) between multiple parties for the purpose of enhancing their digital collaboration.

Eastman et al. (2010) and Aram et al. (2010) suggested the notion of exchange objects to replace exchange requirements of ISO 24981-1. Consequently, the IDM becomes decoupled from IFC. Both Eastman et al. and Aram et al. argued that binding data sets (the content of objects and attributes) to a data structure (such as the IFC) should happen through software development (that is, the MVD) rather than by user and domain experts (that is, the IDM). BuildingSMART recently suggested keeping the IDM free of IFC bindings.

The IDM is gaining popularity in the AEC industry and research as a way of re-engineering and modeling processes and information flows.[14] The IDM has been applied in practice (DiKon 2012) and literature (Jeong et al. 2009, Panushev et al. 2010), while suggestions have been made for implementation (Eastman et al. 2010) and improvement (Aram et al. 2010)

8.4.2 The Model Progression Specification

The model progression specification (MPS; AIA 2008) was introduced by the California Chapter of the American Institute of Architects (AIA) as part of the IPD (AIA 2007) framework. The MPS has been further developed by the BIM software vendor Vico Software (Vico 2012) and the US Contractor Webcor (Bedrick 2008). The MPS is a document upon which to agree in a building model. It covers levels of detail, actor, and phase. The MPS does not cover the functional aspect and only partly addresses the behavioral aspect, since it only covers phase rather than sequences and workflow. The organizational and informational aspects are specifically described through level of detail. The major drawback of MPS is its phase-based approach; it describes the information requirements in phase transitions. MPS is also native to BIM.

8.5 Summary

The AEC industry is moving toward BIM supplementation and replacing a tradition of working with documents. The flow of information becomes increasingly important. It is self-evident that

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[14] The BuildingSMART’s IDM website lists 99 IDMs that are currently being developed, of which four are approved. (Karlshoej 2011a)

information needs to be created before it can be used. Previous research in BIM focused on providing the infrastructure for information exchange to fulfill the vision of integrated information. The IFC is one of the outcomes of this. Later research acknowledged the importance of individual actors' information requirements for the task at hand. The IDM of buildingSMART and the MPS of the AIA provide the means to model and document information requirements of individual actors and AEC projects.

9. Information Systems

The research field of information systems (IS) uses the IT artifact as the core subject matter (Orlikowski and Iacono 2001). According to Orlikowski and Iacono's (2001) literature review of 188 articles from 1990–1999, just one-quarter of the articles developed either algorithms or models. Approximately half of the articles discussed the interaction of people with technology in various social contexts, and the rest did not describe, conceptualize, or theorize the IT artifact. Research in design information and information technology (such as BIM) is similar to IS as a socio-technological phenomenon. Therefore, IS can serve as field of reference. Traditionally, IS has thought of other disciplines as a reference for IS research. However, IS can become a reference for other fields of research (engineering, for example), both through knowledge in the field and methodological choices as it matures (Baskerville and Myers 2002). The background of IS introduced and defined. The section then discussed why BIM is an IS. Research methodology that can inform this research is then introduced. Finally, the paper presents the notion of information quality, as it informs the observed problem and research scope.

9.1 Background

IS is a topic of research in many different fields, from social sciences to natural and computer sciences (Khazanchi and Munkvold 2000). Nevertheless, it lacks an agreed-upon definition. Paul (2007) identified this as one of five challenges for the IS field. Carvalho (1999) argued that the term *IS* refers to four different objects:

1. An organization that delivers information (libraries, newspapers, TV stations).
2. A subsystem within an organization that ensures communication between operations and management.
3. Any system that processes information using computers, and can automate organizational work that deals with information (workflow management systems, data mining systems, data processing systems).
4. Any system that processes information. This view corresponds to all organizational activities excepting those that deal with materials or energy.
   (Carvalho 1999)

Thus, an IS can be an organization or different kinds of systems that communicate or process information, with or without the use of technology (Carvalho 1999). Furthermore, IS can be seen from a purely technological aspect, a socio-technical perspective, and a pure sociological perspective (Orlikowski and Iacono 2001). It comes as no surprise that "Many definitions have been proposed over the years by researchers and textbook authors, but most are viewed as unsatisfactory for one reason or another" (Alter 2008). The scale ranged from social or organizational concerns to technical or conducted a literature review and sorted IS mathematical concerns. The following two quotes represent the outer marks of this scale. The extreme of social aspects is represented by:

> *An information system is a social system, which has embedded in it information technology. The extent to which information technology plays a part is increasing rapidly. But this does not prevent the overall system from being a social system, and it is not possible to design a robust, effective information system, incorporating significant amounts of the technology without treating it as a social system.*

Land 1985, in Alter 2008

The extreme technical aspect is represented by:

> *An information system is a data table, whose columns are labeled by attributes, rows are labeled by objects of interest and entries of the table are attribute values.*
> Pawlak 2002 in Alter 2008

9.1.1 An IS Definition

Alter (2008) introduced the concept of work systems to define IS. Alter argued that business organizations contain a multitude of work systems, such as “procure materials from suppliers, manufacture physical and/or informational products, deliver products to customers, find customers, create financial reports, hire employees, coordinate work across departments, submit tax payments, and perform many other functions.” Accordingly, he proposed the following definition for a work system:

> *A system in which human participants and/or machines perform work (processes and activities) using information, technology and other resources to produce specific products and/or services for specific internal or external customers.*
> (Alter 2008)

In IS, processes and activities are devoted to information. Alter (2008) defined IS as:

> *A system in which human participants and/or machines perform work (processes and activities) using information, technology, and other resources to produce* ***informational*** *products and/or services for internal or external customers.*
> (Alter 2008)

The general definition of *work system*, as well as the special definition of IS, is based on several elements. Participants perform the non-automated work. Processes and activities can be highly structured workflows or artful processes whose sequence and content depend on the skills, experience, and judgment of the primary actors (Hill et al. 2008). Information can be codified or non-codified. Technology is not necessarily limited to IT because multiple technologies may be relevant. Resources include infrastructure, products, and services. These are a combination of physical things, information, and services. Customers are direct beneficiaries, as well as people whose interest and involvement is less direct. Alter’s (2008) definition fits the four types of objects identified by Carvalho (1999).
Furthermore, Alter (2008) distinguished between IS and IT reliant work systems: “The fact that a work system uses information technology (IT) extensively does not imply that it is an IS.” An IS is a special type of IT-reliant work system. IT-reliant work systems can have any kind of product or service as output, whereas IS has information, informational products, or services as its output.

9.1.2 An IS for Design Information

If design information is collected in a BIM building model, IT is extensively used. Design information is processed in an IT-reliant work system, as defined by Alter (2008). The output is information, so it is an IS. To discuss the applicability of IS literature to research in BIM further, the following draws on Alter’s (2008) definition of IS to argue why BIM can be seen as an IS. Alter’s definition builds on seven elements: participants, machines, work, information, technology, products and services, and customers. Each of these is related to BIM.

Participants in an IS perform non-automated parts. The primary participants providing informational input to the building model are the client and design team, architects, and engineers. Building-product manufacturers also provide information. The general contractor and subcontractors also provide relevant information to the building model. In BIM, work is primarily conducted by human participants, rather than *machines.*

Among the *work* (processes and activities) that BIM supports are analysis, simulations, and calculations related to design, planning, and execution of construction work.

Information is the data and knowledge that constitutes the digital and non-digital input for the IS. In an integrated BIM, the first information collected is the client requirements. The system should capture ongoing information from participants during design, planning, and execution of construction work.

Technologies are the software and hardware utilized in the systems. An integrated BIM contains a multitude of software and hardware. One or more digital models are built by BIM software. The digital model is placed on a server and accessed from computers, hand-held devices, and mobile phones via software. Technologies can also be sensor data, such as RFID tags or automatic registration processes of other kinds.

Products and *Services* are the informational output of the IS. In the case of BIM, there is traditional output such as drawings, schedules, specifications, and work descriptions. New products are the numerous visualizations of analysis and simulations. Services are a consolidation of the digital model and tracking building products, construction progress, and costs.

Customers are the benefactors of the system. In an integrated and collaborative BIM system, most participants are also customers because they benefit from the information produced by other participants. It is noteworthy that Alter’s (2008) definition of an IS includes the informational products and services delivered to customers. Accordingly, BIM is a special case of IS in the AEC industry.

9.2 Research Paradigms in IS

The IS field brings together natural and social sciences, positivistic, and interpretivist research paradigms, and quantitative and qualitative methods (Gregor 2006). IS research is often applied and tightly connected to its environment. Consequently, it exists between its environment and base of knowledge (see Figure 9-1). The IS environment includes practitioners who plan, manage, design, implement, operate, and evaluate IS and their organizations. The knowledge base of IS is the existing research within the paradigm. Research in IS develops and builds theories and artifacts that are justified and evaluated. The environment defines the problem space in which the phenomena of interest reside. This environment is composed of people, organizations, and their technologies. Under this are the goals, tasks, problems, and opportunities that define business needs as they are perceived by people within the organization (Hevner et al. 2004).

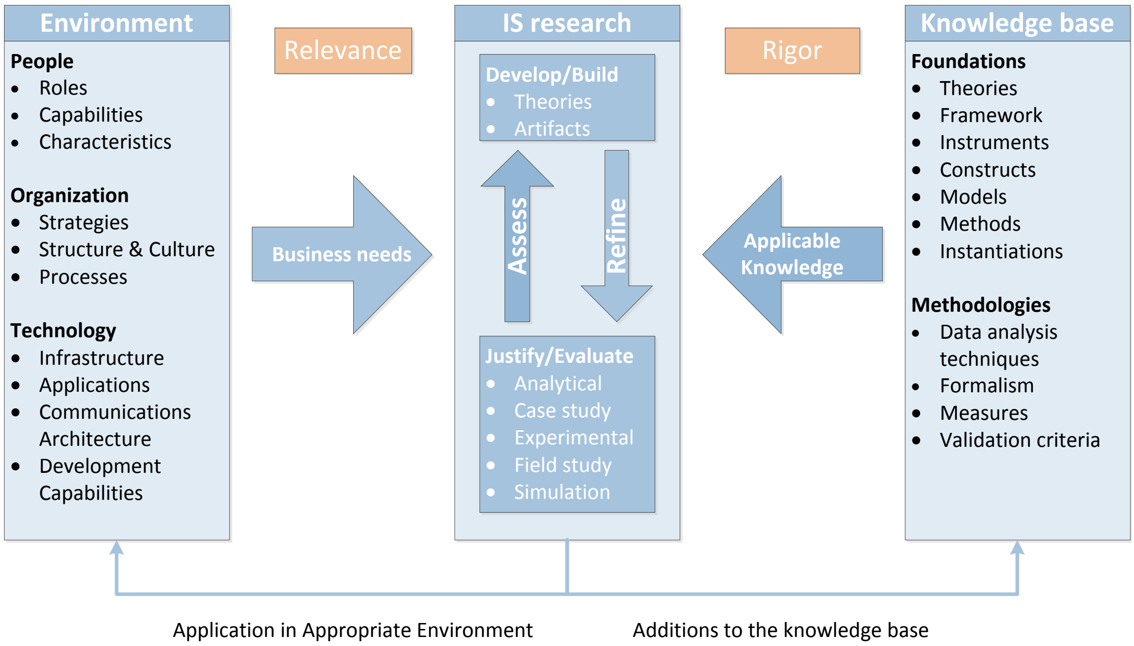

Figure 9-1: Information Systems Research Framework (Hevner et al. 2004).

A major concern in the IS field is the lack of shared theory. This has led to theorizing the IT artifact (Orlikowski and Iacono 2001) and developing an IS shared theory or multiple theories (Weber 2003). Gregor (2006) suggested a taxonomy of five theory types, relevant for the IS field:

1. **Analysis** – Says what is. The theory does not extend beyond analysis and description. No causal relationships among phenomena are specified, and no predictions are made.
2. **Explanation** – Says what is: how, why, when, and where. The theory provides explanations, but does not aim to predict with any precision. There are no testable propositions.
3. **Prediction** – Says what is and what will be. The theory provides predictions and has testable propositions, but does not have well-developed justificatory causal explanations.
4. **Explanation and prediction (EP)** – Says what is: how, why, when, where, and what will be. Provides predictions and has both testable propositions and causal explanations.
5. **Design and action** – Says how to do something. The theory gives explicit prescriptions (for example, methods, techniques, principles of form and function) for constructing an artifact.
   (Gregor 2006)

These types of theories are interrelated. The basic analytic theory is necessary to form other types of theory. Design and action theory are strongly interrelated with EP theory. Design theory implements results from EP. Likewise, EP is tested by implementation through design theory. Both design theory and EP are the highest level of theory and are informed by all the other types of theory. The first four of Weber’s types of theory belong to a natural and social science paradigm. However, design and action types of theory are in the design science paradigm.

9.2.1 Design Science

Design science is the science of the artificial. It opposes the natural sciences by creating things that serve human purpose, rather than trying to understand reality (March and Smith 1995). A major concern is whether design science can produce theory. March and Smith (1995) claimed that theorizing has a natural-science intent, and does not belong in design science. Instead, design science can validate natural science theories:

> *Natural science theories receive confirmatory support from the facts that bridges do not collapse, medical treatments cure diseases, people journey to the moon, and nuclear bombs explode.*
>
> (March and Smith 1995)

Baskerville and Pries-Heje (2010) divided design theory into explanatory and practice theories. Explanatory design theory is descriptive and "provides a functional explanation as to why a solution has certain components in terms of the requirements stated in the design" (Baskerville and Pries-Heje 2010). Gregor (2006) argued that prescriptive research in design science can also produce theory. Gregor identified the following components that constitute a theory:

- **Means of representation** – the physical representation
- **Constructs** – the phenomena of interest
- **Statements of relationship** – relationships among the constructs
- **Scope** – the degree of generality of the statements of relationships
- **Causal explanations** – statements of relationships among phenomena that show causal reasoning
- **Testable propositions (hypotheses)** – statements of relationships between constructs in a form that enables them to be tested empirically
- **Prescriptive statements** – specify how people can accomplish something in practice
  (Gregor 2006)

According to Gregor (2006), the five different types of theory (that is, analysis, explanation, prediction, explanation and prediction, and design and action as described earlier) have different emphases within these components. Hevner et al. (2004) identified the products or artifacts of design science, which are built and evaluated within this paradigm as the contribution to knowledge:

- **Constructs** – vocabulary and symbols
- **Models** – abstractions and representations
- **Methods** – algorithms and practices
- **Instantiations** – implemented and prototype systems.
  (Hevner et al. 2004)

According to March and Smith (1995), the contribution to knowledge of design science products "lies in the novelty of the artifact [constructs, models, methods and instantiations] and in the persuasiveness of the claims that it is effective." *Novelty* is being the first within the discipline. Novel constructs, models, and methods are contributions, but novel instantiations are not. March and Smith (1995) further argued that the first, novel artifact is not subject to performance evaluation, but must have "utility for an important task." The second artifact needs to provide significant productivity improvements through explicit metrics. Drawing on this, Hevner et al. (2004) suggested guidelines for design-science research:

- **Design as an Artifact** – Design-science research must produce a viable artifact in the form of a construct, model, method, or instantiation.
- **Problem Relevance** – The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
- **Design Evaluation** – The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
- **Research Contributions** – Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, foundations, and/or methodologies.
- **Research Rigor** – Design-science research relies upon the application of rigorous methods in both construction and evaluation of the design artifact.
- **Design as a Search Process** – The search for an effective artifact requires the utilization of available means to reach desired ends while satisfying laws in the problem environment.
- **Communication of Research** – Design-science research must be effectively presented to both technology and management audiences.
(Hevner et al. 2004)

Design evaluation can be observational (case study and field study), analytical (static analysis, architecture analysis, dynamic analysis, and optimization), experimental (controlled experiment or simulation), testing (functional or structural), and descriptive (informed argument or scenarios). According to Hevner et al. (2004), research contributions in design science are the design artifact (novelty or performance improvement), foundations (appropriately evaluated constructs, models, methods, or instantiations), and methodologies (measures and evaluation metrics). Research rigor is derived from the effective use of the knowledge base of theoretical foundations and research methodologies (Hevner et al. 2004).

Engineering research also discusses design science. Eekels (2000, 2001) noted that engineering design research goes beyond understanding by improving the process, in a manner similar to the one presented above. Eekels described that the object of engineering design research is the action object (thing, situation, process leading, body of knowledge, or information), the action subject (single person, co-operating team, or organization), and the action process (interaction between the action subject and the object acted upon). However, while IS-design science is largely prescriptive (as descriptive research is attributed to natural and social science paradigms within IS), engineering design science also allows for descriptive work. The descriptive part of engineering design science contributed to Baskerville and Pries-Heje's (2010) notion of explanatory design theory.

9.2.2 Action Research

The design science paradigm seems closely related to action research methodology. Baskerville and Wood-Harper (1996) described action research by three distinctive characteristics:

- The researcher is actively involved, benefiting both the researcher and the organization.
- The obtained knowledge can be immediately applied. There is a sense of the active participant utilizing new knowledge based on an explicit, clear, conceptual framework.
- The research is a cyclical process linking theory and practice.
(Baskerville and Wood-Harper 1996)

Design science has its origins in the work of engineers, architects, and the field of IS. Action research comes from the field of applied anthropology. Jarvinen (2007) identified seven fundamental characteristics of action research and six of design science (see Figure 9-1). In comparing these, Jarvinen suggested that design science and action research are similar in method, output, and the desire to contribute to knowledge and practice.

Action research	Design Science
AR-1: Action research emphasizes the utility aspect of the future system from people's point of view.	DS-4: Design science's products are assessed against criteria of value or utility.
AR-2: Action research produces knowledge to guide practice in modification.	DS-2: Design science produces design knowledge (concepts, constructs, models, and methods).
AR-3: Action research means taking action and evaluating.	DS-3: Building and evaluation are the two main activities of design science.
AR-4: Action research is carried out in collaboration between an action researcher and the client system.	DS-5: Design-science research is initiated by researcher(s) interested in developing technological rules for an issue. Each individual case is primarily oriented at solving the problem in close collaboration with people.
AR-5: Action research modifies a given reality or develops a new system.	DS-1: Design science solves construction problems (producing new innovations) and improvement problems (improving performance of existing entities).
AR-6: The researcher intervenes in the problem setting.	DS-5: Design-science research is initiated by the researcher(s) interested in developing technological rules for an issue. Each individual case is primarily oriented at solving the problem in close collaboration with people.
AR-7: Knowledge is generated, used, tested, and modified in the course of the action research project.	DS-6: Knowledge is generated, used, and evaluated through the building action.

Table 9-1: Similarities of the fundamental characteristics of action research and design science (Jarvinen 2007)**.**

Baskerville (2008) argued that, while design science and action research may look similar, they are not:

> *Action research is focused on problem solving through social and organizational change. Design science is focused on problem solving by creating and positioning an artifact in a natural setting. Action research is clearly centered on discovery-through-action. Design science is clearly centered on discovery-through-design. Action research is a methodology. Design science is a paradigm.*
>
> (Baskerville 2008)

However, action research can be a methodology within IS design research, such as "to study the effects of specific alterations in systems development methodologies" (Baskerville and Wood-Harper 1996).

9.3 Information Quality

Data and information are essential parts of an IS. Information is the input, the object of action, and the output (cf. Alter's (2008) definition in Section 9.1.1). Information quality is an established area of research in IS and related fields. Information quality is "consistently meeting knowledge-worker and end-customer expectations" to enable accomplishment of personal objectives (English 1999).

9.3.1 Quality

Understanding the term *quality* is important for understanding information quality. Quality is perceptual, conditional, and subjective, since the individual puts meaning in to the term. Hence, further definition is needed. Product and service quality are an important part of production-management approaches such as total quality management (Dean Jr. and Bowen 1994), lean production (Womack et al. 2007), and six sigma[15] (Linderman et al. 2003). Non-inferiority or superiority are pragmatic definitions of quality. *Fitness for use* is another common definition that was promoted by Juran (1979). *Fitness for use* was later adjusted by Juran and De Feo (2010) to *fitness for purpose*, to take into account quality of both services and products. Six sigma provides quantitative measures to define quality. The target is to achieve less than 3.4 deviations per million (Hahn and Hill 1999).

Drawing on a literature review, Reeves and Bednar (1994) identified four definitions of quality excellence, value, conformance to specifications, and meeting and/or exceeding customers' expectation. The latter two definitions address two characteristics of quality that are worth noting. First, it is essential to specify quality criteria. Conformance to specification emphasizes that quality can only be achieved if requirements are explicit (for example, six sigma uses upper and lower service limits to specify quality requirements). The second is that the customer defines quality. Meeting and/or exceeding customers' expectation emphasizes that the receiver and user of the process output defines quality. *Customer* does not necessarily refer to external or end customers; it can be internal customers who further process the output of a subsequent.

9.3.2 Dimensions of Information Quality

Juran's fitness-for-use definition informed Wang and Strong (1996) definition of information[16] quality as "data that are fit for use by data consumers." Wang and Strong further stated that data quality "must be considered within the context of the task at hand."

Wang and Strong (1996) argued that understanding users' problem with data is essential for understanding information quality. They identified the following four categories and 14 dimensions of information quality:

- **Intrinsic** – believability, accuracy, objectivity, and reputation
- **Contextual** – value-added, relevancy, timeliness, completeness, and appropriate amount of data
- **Representational** – interpretability, ease of understanding, representational consistency, and concise representation
- **Accessibility** – accessibility and access security
  (Wang and Strong 1996)

Ballou and Pazer (1985) identified timeliness, accuracy, completeness, and consistency as dimensions of information quality. A literature review of 12 journals[17] identified 85 articles that de-

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[15] Six sigma is a production-management strategy that seeks to improve the quality of process outputs by statistical methods. The goal of six sigma is to produce within the specification limits for six standard deviations (sigma; 99.99966%) of the production.

[16] Like many others, Wang and Strong (1996) refer to data rather than information. However, data and information are used almost interchangeably in IQ research. In the early days of IQ research, data was preferred over information. Information seems to be more recently preferred in the literature.

[17] *Communications of the ACM, Journal of Information Science, Journal of Management Information Systems, Information Systems, IEEE Transactions on Knowledge and Data Engineering, Journal of the American Society for Information,*

scribed information-quality frameworks. Almost half of these frameworks can be directly related to the work of Wang and Strong (1996). This is even more applicable for Ballou and Pazer (1985), since Wang and Strong covered their work.

Appearances	**Dimension**
59	Accuracy
49	Completeness
41	Timeliness
39	Consistent
33	Relevance
23	Accessible, Understandability
17	Currency, Interpretability, Objectivity
16	Believability
15	Appropriate Amount of Data, Reliable
14	Concise, Security
13	Value-Added
12	Reputation
9	Format
8	Comprehensive
7	Correctness, Usefulness
6	Authority, Ease of Manipulation, Free of Error
5	Clarity, Informativeness, Precise

Table 9-2: Most frequently cited dimensions of information quality in the literature, based on 12 journals.

One of the most influential studies of information quality in the AEC industry was conducted by Tilley and McFallan (2000a, 2000b). They surveyed both designers' and contractors' perceptions of information quality, according to predefined dimensions. The dimensions were: accuracy, certainty, clarity, completeness, conformity, coordination, final checking, relevance, standardization, and timeliness. Furthermore, it is interesting to note the significant difference between contractors' and designers' perceptions of information quality, as well as professionals' perception of information quality, declines over time. The research of Tilley and McFallan was replicated by Andi and Minato (2003) in the Japanese AEC industry. Further research in the AEC industry was conducted by Westin and Päivärinta (2011), who examined information quality by identifying 125 general problems within a large engineering and construction company, Laryea (2011) analyzed the quality of UK tender documents. In earlier work, Tilley (1997) measured the quality of design information using requests for information (RFIs).

9.4 Summary

IS research is a relatively new field that ranges technological and socio-technological systems, to pure sociological considerations. IS has traditionally looked to other fields for reference. It has now matured to the point where it can serve as reference for other research areas. As a new field of research, BIM may profit from looking into IS research. Particularly interesting is the paradigm of design science as interpreted in IS. The research within BIM is often prescriptive without being explicit about operating in the design-science paradigm. This section discussed

Science and Technology, Information & Management, Journal of Computer Information Systems, Information and Software Technology, Management Information Systems Quarterly, Journal of Database Management, IEEE Transactions on Engineering Management whether design science can produce theory and whether it is desirable for non-positivistic research to produce theory. It is clear that design science and prescriptive research can contribute to knowledge under certain circumstances. Contribution is based on novelty, performance, and practical problem-solving. Furthermore, Hevner et al.'s (2004) guidelines for design-science research can serve as reference. Action research is related to design science, but is a methodology rather than a paradigm. Hartmann (2009) suggested a combination of action research and ethnographic research as a method for developing and implementing IS (BIM) among AEC practitioners.

Information quality is a subfield of IS that posits information quality is a multidimensional phenomenon that goes beyond accuracy. Many authors have studied information quality. Much of it can be related to the work of Ballou and Pazer (1985) and Wang and Strong (1996).

10. Socio-technical Systems

Design information created by BIM methods constitutes an IS for AEC projects (cf. Section 9.1.2). This type of technological system is placed in the context of an organization. A work system in which technology interacts with people is referred to as a *socio-technical system*. Such systems can be studied from many perspectives. Pure technological systems and pure social systems exist at either end of the perspective spectrum. The socio-technical perspective lies between the two:

- **Technological** – the focus is on technology and the social perspective is neglected, for example, by developing models, algorithms, and hardware composition that improve the computational efficiency or functionality of the system.
- **Social** – the focus is on the social situation and the technology is absent, for example, by studying relationships and interactions within the organization.
- **Socio technical** – acknowledges both the technology and the people working with it, and seeks to understand both.

The following section introduces research paradigms that seek to understand both technology and the social situation within which the technology is placed. The focus of this study's design information quality is also between realms of the technological and social. The purpose is to inform the methodology of this thesis and provide underlying theories that combine the technological and social aspects of the research scope. First, the epistemological background for these research paradigms is introduced. The social studies of technology are discussed generally. Finally, the social construction of technology is discussed specifically.

10.1 Social Constructivism

Immanuel Kant (1781) posited a central question in the philosophy of science in his influential work "Kritik der reinen Vernunft" [Critique of Pure Reason]:

> *Was kann ich wissen?*
> [What can we know?]
> (Kant 1781)

In his answer to this central question and the implied question *what is knowledge*, Kant separated the world as it is in itself (*noumena*) from how it presents itself to us (*phenomena*). We can only know (*erkenntnis*) about phenomena within the limits of our human experience (Campbell 2002). According to Kant, reason (*verstand*) associates the world as we sense it with pre-existing categories.

> **I see** a creature with four legs.
> **I reason** it is a poodle.
> **I know** it is a dog – a mammal – an animal.

Our mind puts the observation into categories and connects it to our knowledge about it. Kant's thoughts are the basis of constructivism, which assumes that "the world cannot be known directly, but rather by the construction imposed on it by the mind" (Young and Collin 2004). Constructivism opposes positivism and realism. Positivists and realists believe that the world exists independently of the observers and can be described by science. Fuller (2003) defined constructivism and the related relativism as a denial of scientific realism:

1. *A scientific account is universally valid. Therefore, if scientific theory T is true, it is true everywhere and always. The denial of this claim is relativism. It implies that reality may vary across space at any given time.*
2. *A scientific account is valid independently of what people think and do. Therefore if T is true, it is true even if nobody believes it. The denial of this claim is constructivism. It implies that, for a given place, reality may change over time.*

(Fuller 2003)

The perception of reality (Kant's phenomena) changes over time. What imposes this perception is a central question. Consequently, there are different types of constructivism; Young and Collin (2004) identified three types:

- **Radical constructivists** – the individual mind constructs reality.
- **Moderate constructivists** – individual constructions take place within a systematic relationship to the external world.
- **Social constructivists** – the influence on the individual construction is derived from, and preceded, by social relationships.
(Young and Collin 2004)

Constructivism has a dualist assumption, such as Kant's phenomena and noumena perception of reality. Even radical constructivists do not neglect the existence of a mind-independent reality (noumena), but they believe it cannot be known.
Social constructivism is closely related to social constructionism, which is often seen in studies of societal influence. Social constructivism and social constructionism are sometimes used interchangeably,[18] and the differences between them are not always evident. Advocates of both philosophies believe in the influence of the social on reality. According to Young and Collin (2004):

> [Social constructionism] *contrasts with it* [social constructivism] *in having a social rather than an individual focus [and] it is less interested, or not at all interested, in the cognitive processes that accompany knowledge.*
>
> (Young and Collin 2004)

Social constructivism has its roots in positivism and has a dualist assumption, although phenomena and noumena are not always apparent (Young and Collin 2004). Social constructionism, on the other hand, is in the hermeneutic tradition. There is no knowledge beyond individuals' subjective and inter-subjective interpretations of reality (Lindgren and Packendorff 2009). They are both used in different sociological fields, but social constructionism is more common in the field of psychology (Young and Collin 2004, Puig et al. 2008).
The misconception that social constructivism and social constructionism are identical could be that much work in humanities and sociology is related to the social construction of phenomena. However, describing the world as socially constructed is not specific to social constructionism. Social constructivists or even plain constructivists also work with this topic. These two fields are

[18] A Google search in May 2012 for the term *social constructionism* returned results concerning both social constructionism and social constructivism.

sometimes lumped together, especially when being criticized, because they are so closely related.
Boghossian (2001), who has been critical of social constructivism, described the social constructivist claim as follows: “The correct explanation for why we have some particular belief has to do with the role that that belief plays in our social lives, and not exclusively with the evidence adduced in its favor.” For a social constructivist, theory is “some sort of representation of a phenomenon, for example a set of beliefs about a particular phenomenon” (Mallon 2007). This rather superficial definition includes not only scientific theories, but also theories that are held by individuals or groups (such as folk theories). Fuller’s (2003) definition of constructivism and Mallon’s (2007) definition of theory include all knowledge and beliefs a society has. These beliefs, whether scientific or nonscientific, are influenced by the social context and their pre-existing knowledge and categories. “Scientific knowledge itself had to be understood as a social product” (Pickering 1992).
Social constructivist theory studies scientific and common beliefs. Beyond that, more provocative constructivist studies concern the social construction of the objects to which those theories refer (Mallon 2007). According to Boghossian (2001), the core idea of social construction of objects is:

> *This thing could not have existed had we not built it; and we need not have built it at all, at least not in its present form. Had we been a different kind of society, had we had different needs, values, or interests, we might well have built a different kind of thing, or built this one differently.*
>
> (Boghossian 2001)

Objects shaped through social interaction are contrary to naturally existing objects that are independent of their context, as in realism. Money is an example of a social construction.[19] Neither citizenship nor the presidency would exist without society; they exist because people believe in them. Phenomena that existed before societies are also socially constructed. Two such examples are dinosaurs and quarks[20] (Boghossian 2001). Even mental illness (Mallon 2007) is seen as socially constructed.
To understand the social construction of objects, it is necessary to divide the notion of social construction of objects in half. As Mallon (2007) explained: “one centered on our ways of thinking about, representing, or modeling the world, and the second centered on parts of the world itself.” The world is divided into *noumena* (objects as they are) and *phenomena* (objects as we can think of them). A radical constructionist does not believe in a mind-independent world, claiming instead that everything is constructed. Moderate social constructivists theorize that phenomena is constructed and shaped by society and the meaning it gives them. While there is

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[19] The value of money is not derived (intrinsic) from the value of the materials, but attributed by the people trading with it.

[20] Quark: any member of a group of elementary subatomic particles that interact by means of the strong force and are believed to be among the fundamental constituents of matter. Quarks associate with one another via the strong force to make up protons and neutrons, in much the same way that the latter particles combine in various proportions to make up atomic nuclei. There are six types, or flavors, of quarks, which differ from one another in their mass and charge characteristics (*Encyclopedia Britannica*).

evidence for the existence of dinosaurs, society attributes the status and role of dinosaurs on the basis of its experiences and beliefs.
Constructivism opposes scientific realism. In the 1990s, it led to a war on the nature of scientific theories between scholars on each side (that is, the science wars). As part of this, the concept of social construction of objects was criticized. One of the critiques addressed the denial of universal truth. Boghossian (2006) tried to expose constructivism by reduction ad absurdum:

> a. Since we have constructed the fact that P, P exists.
> b. Since it is possible that another community constructed the fact that not-P exists, then possibly not-P exists.
> c. So it is possible that both P and not-P exist.
>
> Of course, there is no possible world in which both P and not-P exist. The law of non-contradiction is inviolable.
> (Boghossian 2006)

Social constructivists are also criticized for having a political agenda by their critiques: "The content of theories is determined by the self-interest of the powerful (for example, of the wealthy, white, or male) in retaining their power" (Mallon 2007).

10.2 Studies of Technology

Technology is one object that constructivist scholars have studied. In 1984, scholars from the early science-technology-society movement,[21] the sociology of scientific knowledge,[22] and the history of technology[23] met at a workshop in the Netherlands. The result was a book called *The Social Construction of Technological Systems* (Bijker et al. 1987). This workshop is the starting point for constructivist studies of socially constructed technology, and the book became an influential piece. Three approaches to constructivist studies of socially constructed technology were presented at this workshop: SCOT (Pinch and Bijker), Actor Network Theory (ANT) (Latour, Callon and Law), and Systems Approach (Hughes).
All three approaches have a common ground. First, they oppose technological determinism. Scholars of technological determinism claim that technology develops linearly and that technology determines society, rather than the other way around. Even though Marx is generally not considered a technological determinist (Bimber 1990), the following quote could be interpreted as technological determinism:

---

[21] Science-technology-society movement (STS) "*started in the 1970s. Its goal was to enrich the curricula of both universities and secondary schools by studying issues such as scientists' social responsibilities, the risks of nuclear energy, the proliferation of nuclear arms, and environmental pollution. The movement was quite successful, especially in science and engineering faculties, and some of the STS courses became part of the degree requirements*" (Bijker 2010).
[22] "*The sociology of scientific knowledge (SSK) emerged in the late 1970s in the UK on the basis of work in the sociology of knowledge, the philosophy of science, and the sociology of science (Bloor, 1976; Collins, 1981, 1985). The central methodological tenets of the strong programme (especially its symmetry principle) seemed equally applicable to technology*" (Bijker 2010).
[23] "In the history of technology, especially in the USA, an increasing number of scholars began to raise more theoretical and sociologically inspired questions (influential were Hughes, 1983, and Cowan, 1983). Path-breaking advocacy for this body of work in the history of technology provided the reader edited by MacKenzie and Wajcman (1985)" (Bijker 2010).

Die Handmühle ergibt eine Gesellschaft mit Feudalherren, die Dampfmühle eine Gesellschaft mit industriellen Kapitalisten.
[The windmill gives you society with the feudal lord: the steam-mill, society with the industrial capitalist]
(Marx 1885)

Heinbroner (1967) drew on this Marx quotation to support his view of linear development: "The steam mill follows the windmill not by chance but because it is the next 'stage' in a technical conquest of nature that follows one and only one grand avenue of advance."
A common example of linear development of technology is Moore's Law[24] (Tuomi 2002, Ceruzzi 2005) about the doubling of computer power every 18 months. Cerruzi (2005) argued that the public acceptance of technological determinism is quite high, especially when it comes to information technology and software. People tend to accept technology uncritically without regard to context and social dimension.
Second, SCOT, ANT and the systems approach try to open the black box of technology. This means that other sociological studies have analyzed technology as input and output, assuming that the technology is working. *Black boxing*, according to Latour (1999), is the way scientific and technical work is made invisible by its own success:

When a machine runs efficiently, when a matter of fact is settled, one need focus only on its inputs and outputs and not on its internal complexity. Thus, paradoxically, the more science and technology succeed, the more opaque and obscure they become.
(Latour 1999)

Bijker et al. (1987) described opening the technological black box of thick descriptions and detailed information about the technical, social, economic, and political aspects, instead of treating technology or society as black boxes.
Third, there is a focus on actors (ANT) and social groups (SCOT) forming networks that struggle and negotiate to form the technology. Winner (1993) praised social constructivism for "its conceptual rigor, its concern for specifics, its attempt to provide empirical models of technological

[24] Moore's law, after Gordon E. Moore. In April 1965, Moore, then the director of research and development at the semiconductor division of Fairchild Camera and Instrument Corporation, published a paper in which he observed that the number of transistors that could be placed on an integrated circuit had doubled every year since integrated circuits had been invented and predicted that that trend would continue. Shortly thereafter, Moore left Fairchild to cofound Intel, a company that, as Bassett notes, staked its future on MOS technology (Ceruzzi 2005). This exponential increase in the number of components on a chip became later known as Moore's Law. In the 1980s, Moore's Law started to be described as the doubling of number of transistors on a chip every 18 months, at the beginning of the 1990s; Moore's Law became commonly interpreted as the doubling of microprocessor power every 18 months. In the 1990s, Moore's Law became widely associated with the claim that computing power at fixed cost is doubling every 18 months (Tuomi 2002). Nonetheless, Moore's prediction that the number of transistors that could be placed on an integrated circuit would continue to double at short, regular intervals has held true ever since, although the interval soon stretched from 12 to 18 months. Analysts have been predicting the failure of Moore's law for years. Interestingly, the moment of its demise seems always to be about 10 years from whenever the prediction is made; that is, those writing in 1994 anticipated that it would fail in 2004, while some today put the likely date at about 2015 (Ceruzzi 2005).

change that better reveal the actual course of events." However, Winner has four points of criticism:

1. *The social consequence of technical choice is left out.*
2. *It is unclear who defines relevant social groups, and how it is assured that silent groups are not left out.*
3. *The possibility is disregarded that there may be dynamics evident in technological change beyond those revealed by studying the immediate needs, interests, problems, and solutions of specific groups and social actors.*
4. *The research is conducted without taking a stand on the larger questions about technology and the human condition that matter most in modern history.*

(Winner 1993)

Social constructivist studies on society and technology, and technological determinism, contribute to multidisciplinary research on the social, political, and cultural values that affect scientific research and technological innovation. This field is called Science and Technology Studies (STS).

10.3 The Social Construction of Technology

SCOT is ascribed to Trevor Pinch, professor at Cornell University, and Wiebe Bijker, professor of Social Science and Technology at Universiteit Maastricht. The birth of SCOT is typically assigned to the 1984 workshop (cf. Section 10.2). SCOT is in a social constructivist tradition, but treats technical factors in a relativist fashion (Pinch and Bijker 1986). In *The Social Construction of Technological Systems,* Pinch and Bijker (1987) described how the influence of different social groups turned the bicycle from the "penny farthing" to the bicycle we know today.

In SCOT, the developmental process of a technological artifact is described as an alternation of variation and selection. This results in a "multidirectional" model, in contrast with the linear models used explicitly in many innovation studies and implicitly in much history of technology (Pinch and Bijker 1987).

The purpose of the multidirectional model is not only to describe the winning technology. It also looks at the discontinued technology. This helps answer the question of why a particular piece of technology or artifact is successful and another vanishes.

10.3.1 Relevant Social Groups

According to SCOT, an artifact has one or more relevant social groups (see Figure 10-1), which can be "institutions, organizations, as well as organized and unorganized groups of individuals, as long as all members share the same set of meaning, attached to a specific artifact" (Bijker 1995).

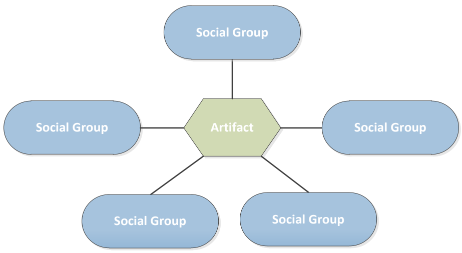

Figure 10-1: The relationship between an artifact and the relevant social groups (Pinch and Bijker 1987).

Social groups can be general, such as users. It might be necessary to break them down into more specific groups:

- AEC Practitioners
  - Engineers
    - Structural engineers
      - Designing with steel structures

This breakdown should be followed for analysis as long as it is necessary to understand the context. Bijker (1995) pointed out two concepts to identify relevant social groups:

1. *Start with interviewing a small group of actors. After each interview, the interviewee is asked who else to interview. By this technique, the number of actors grows like **a snowball that is rolled**. At some point, no new names come up. That is the time to stop.*
2. *Having identified the relevant social group, the next step is to **follow the actors** to learn more about them. This can be a quite straightforward process: because these social groups are relevant for the actors themselves, they typically have described and delineated the groups adequately. After having identified the relevant social groups, it is necessary to describe them into detail, in order to define better the function of the artifact with respect to each group and delineate from other groups.* (Bijker 1995, p 46)

The next step is to look into problems and solutions related to the artifact for the individual social group. "A problem is defined as such only when there is a social group for which it constitutes a 'problem" (Bijker 1995). Social groups can have multiple problems with a technological solution (see Figure 10-2). Each of these problems has different solutions (see Figure 10-3).

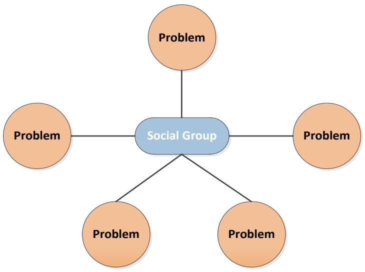

Figure 10-2: The relationship between one social group and the perceived problem (Pinch and Bijker 1987).

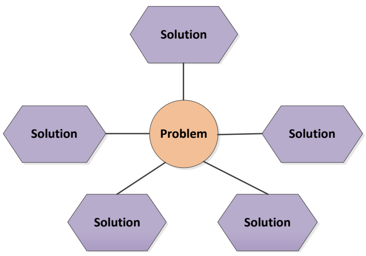

Figure 10-3: The relationship between one problem and its possible solutions (Pinch and Bijker 1987).

10.3.2 In Depth Descriptions

Deep descriptions of the multidirectional development of an artifact a model emerge from the focus on social groups, problems, and possible solutions. This model brings out all types of conflicts, including not just conflicting technical requirements and solutions to the same problem, but even moral conflicts. Bijker (1995) provides an example of a moral conflict:

> *A woman in 1898 is riding a safety bicycle, touring the English countryside. She is wearing knickerbockers, which are practical and comfortable for that purpose. She stops at an inn, but is refused access to the public bar because of her impropriate clothing.*
>
> (Bijker 1995)

Since problems are not purely technical, solutions are not merely technical. Solutions may also be judicial and moral. “In this way [by focusing on the conflicting solutions], one can expect to bring out more clearly the interpretive flexibility of the technological artifacts” (Pinch and Bijker 1987). According to SCOT, the first stage of a new technology is interpretive flexibility.

> *By this we mean not only that there is flexibility in how people think or interpret artifacts but there is also flexibility in how artifacts are designed. There is not just one possible way or one best way of designing an artifact. In principle this could be demonstrated […] by interviews with technologists who are engaged in a contemporary technological controversy.*
>
> (Pinch and Bijker 1987)

Closure and stabilization of an artifact follows interpretive flexibility. At some point, the interpretive flexibility stops, and the winning technological artifact emerges. There are several ways to reach closure. Pinch and Bijker (1987) mentioned two types of closure: rhetorical and redefinition of the problem. It is not necessary to have actually solved the problem in order to reach rhetorical closure. The key point is whether the relevant social groups consider the problem as having been solved. However, it is sometimes necessary to redefine the problem an artifact tries to solve. An example is the air tire of the modern bicycle, which originally addressed a vibration problem on paved roads. However, sporting cyclists could not recognize this problem; they had a hard time accepting the aesthetically distasteful air tires. However, when the air tire was seen as a solution to the sporting cyclists’ concern about how to go as fast as possible, the artifact could reach closure (Pinch and Bijker 1987).
The third stage of SCOT is the wider context. This relates the content of a technological artifact to the sociopolitical milieu. Bijker (1995) referred to this description of the history of a technological artifact as the *descriptive model*. The point of origin is the social deconstruction; the identification and deep description of relevant social groups, such that all social groups are treated equally. Interpretive flexibility is described by looking at the different meaning the relevant social groups give to the artifact. Stabilization emerges from the process of closure.

10.3.3 Technological Frames

Bijker (1995) used the concept of technological frames to make the static descriptive model more dynamic. Technological frames also make it possible to focus on the interaction between social groups and the process of technological change. Bijker (1987) first introduced the concept of technological frames as an explanation for the observation “They [the social group] just did not see it [the emerging technology].” This is an analogy to Kuhn’s (1962)’s paradigm from the book *The Structure of Scientific Revolutions*, which indicates that, from a societal perspective, scholars of SCOT treat the creation of science and technology equally:

> *A technological frame structures the interactions among the actors of a relevant social group. Thus it is not individual’s characteristics, nor characteristics of systems or institutions; technological frames are located between the actors, not in or above actors. If existing interactions move members of a emerging relevant social group in the same direction, a technological frame will be build up; if not, there will be no frame, no relevant social group, no future interaction.*
>
> (Bijker 1995)

A technological frame provides the context in which technology can be developed and accepted by a relevant social group. Having a technological frame means that not everything is still possible, “but the remaining possibilities are relatively clear and readily available to all members of the relevant social group” (Bijker 1995). Not everything can be predicted through the technological frame, due to its degree of inclusion. Actors can be part of different relevant social groups with different degrees of inclusion. Bijker recommended the analyst look at a tentative list of elements contained in a technological frame (see Table 10-1). The list is only tentative because the technological frame is applicable to all types of relevant social groups. Some elements might not be relevant in all cases, as there might be other aspects that are not mentioned (see Table 10-1).

Goals
Key problems
Problem-solving strategies
Requirements to be met by problem solution
Current theories
Tacit knowledge
Testing procedures
Design methods and criteria
User practice
Perceived substitution function
Exemplary artifacts

Table 10-1: Tentative list of elements of a technological frame (Bijker 1995).

In his case studies, Bijker assumed an implicit one-to-one relationship between social group, technological frame, and artifact (see Figure 10-4). This might be sufficient when looking at one artifact. The technological frame provides the vocabulary for social interaction, forming the social group, and the constitution of world and the artifacts. In the world of a relevant social group, there are multiple artifacts. The technological frame links one relevant social group to multiple artifacts. In the semiotic perspective, the technological frame provides a vocabulary for forming artifacts. This does result in one artifact connected to multiple relevant social groups involved in the forming of the artifact through one technological frame (see Figure 10-5).

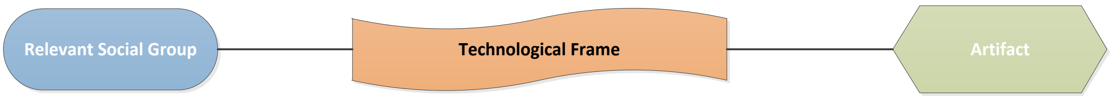

Figure 10-4: Implicitly used relationship between relevant social group, its technological frame, and the artifact (Bijker 1995).

> *By rendering the two sides of analysis – social groups and technical artifacts – into aspects of one world, ‘Technological frame’ will be helpful in transcending the distinction between hitherto irreconcilable opposites: the social shaping of technology and the technological impact on society, social determinism and technical determinism, society and technology.*
> (Bijker 1995)

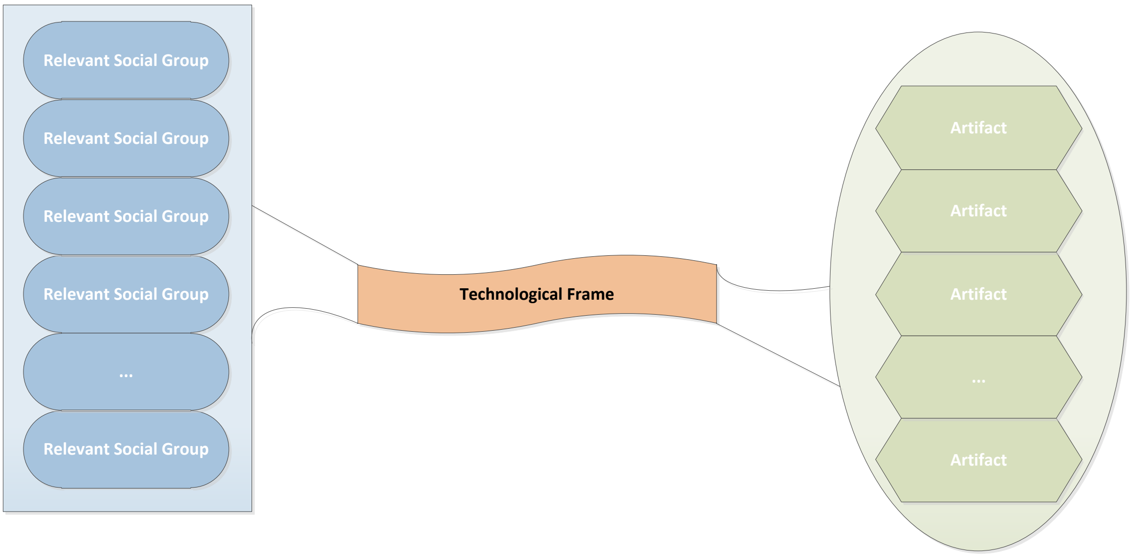

Figure 10-5: The concept of technological frame as a hinge between the social-interactionist and semiotic views of technological development (Bijker 1995).

10.3.4 Criticism of SCOT

Russell (1986) criticized the work of Bijker and Pinch. He found the relativist approach to be analytically inadequate and politically unacceptable, since it potentially entails concentrating on the process of technology creation and neglects content (that is, the artifact). There is also the risk of relativism with respect to social interest; in other words, political neutrality. Russell also noted that it is not always possible to identify all historical alternatives, and that not all social groups have equal power. Consequently, interpretive flexibility lacks a description of power. Finally, parallels with science and technology are not comprehensive because of the unequal power of social groups.

10.3.5 Prescriptive use of SCOT

SCOT provides a descriptive analysis of the development of artifacts in the interaction between technology and people. Many SCOT analyses are retrospective, and describe and explain a sequence of events that led to the design of a technology. The prescriptive and proactive uses in technology design are rather limited. Even though SCOT is intended as a retrospective analysis, the notion of relevant social groups, technical frames, and the progress of technology could be applicable in design science.

Elle et al. (2010) suggested a proactive use of SCOT. They identified technical frames by examining relevant social groups and engaging them in negotiations in so-called *social laboratories*. The purpose was to identify technical frames that could help further development of technology. Social laboratories are workshops in which participants put forward their viewpoints on the topic defined by the researcher. The role of the researcher becomes to:

- Identify and choose the participants.
- Frame the discussion in the invitation and in the agenda.
- Present the arena for discussion in the laboratory; framing the discussion, and setting up the rules for the debate.
- Facilitate the debate.
- Interpret the results of the discussion.
  (Elle et al. 2010)

The researcher can then identify the technological frames put forward in the workshop. These technological frames will then serve as input to the design process. Nevertheless, the prescriptive use of SCOT in the literature is limited.

10.4 Summary and Remarks

This research is between the realms of technology and the social, design information quality, and the social groups that are affected by it. The research proposes a model and method to describe and measure design information quality that is derived in and affects practice. Consequently, this model was considered desirable for treating and involving the people affected by the research in the research.

SCOT was developed to inspire scholars of the social sciences to include technology in their analysis rather than treat it as a black box. For an engineering or design science scholar, it can be tempting to treat the people influencing the technology as a black box. However, engineering and design science scholars looking for how to include social aspects in their research can draw from SCOT. Since SCOT connects the social and technological spheres.

Relevant social groups, their problems and solutions, as well as their technological frames, can guide technology scholars when studying and designing artifacts. The three stages of technology (flexibility, stabilization, and closure) can explain the development of the technology. Another interesting aspect of SCOT is the strong tradition of case studies, such as bicycles, Bakelite, and light bulbs. Furthermore, there are methodological suggestions to follow the actors and roll the snowball. It is a tangible and applicable research paradigm since relevant social groups, technological frames, and fluent technology are very visible. However, SCOT is descriptive and analytical, rather than prescriptive and supportive of artifact creation. SCOT has not yet proven its direct applicability in prescriptive design research. Thus, the importance of relevant social groups on technology is beyond controversy. The influence and significance of the individual group can be difficult to predict, while easier seen retrospectively.

The fact that technology is shaped by people and vice-versa is one of SCOT's important contributions to this research. However, beyond its tangibility for descriptive analysis, it is not as straightforward to apply in the design of artifacts. Therefore, other theory is needed to make it directly applicable in the design of an artifact. Accordingly, this research does not pursue the tradition of social constructivists' studies of technology. The influence of SCOT on this research used the methodological considerations of *rolling the snowball* and *following the actor*. In addition, considering SCOT provided a theoretical background to oppose a deterministic approach to technology. People, in the form of relevant social groups, actors, and practitioners, had a great part in output design. SCOT inspired the author not to ignore the social or technological aspects of a socio-technical system. Consequently, this research draws on design science from information for theoretical inspiration and guidance, which will be discussed in detail in Section 13.

Part III – Research Design

Part III discusses the research design. Based on Parts I and II, this part identifies research questions and identifies research quality criteria. This section also summarizes the method and findings of the research tasks described in detail in the respective papers.

11. Research Question

This research places itself in the intersection between BIM and construction management; specifically, design management in the AEC industry. The research draws on findings from research in information quality and information systems. These findings provided theoretical knowledge to inform the research questions. The research questions based on the theoretical point of departure are discussed below.

Like many information systems, BIM has the inherent and implicit promise of better information; specifically, for BIM it is better design information. The pursuit of better design information is rooted in the assumption that it will lead to better design, planning, and execution of construction work. Evidence from other industries suggests that information systems improve productivity (Banker et al. 2006), and information management improves performance (Mithas et al. 2011). Better design, planning and execution of construction work are criteria for better output, such as the final building (fewer defects) or the construction process (fewer budget overruns or delays related to design information). The literature shows a relationship between design information quality (Josephson and Hammarlund 1999), budget overruns (Reichelt and Lyneis 1999), and schedule delays (Sullivan and Harris 1986). However, it is not the scope of this research to discuss criteria for better design, planning, and execution of construction work.

The objective of this research is to achieve better design information that will potentially lead to better outcome of the construction work. In order to achieve this design information, quality needs to be described and measured. Criteria for better design information in the AEC industry have yet to be defined. There is no consistent and accepted definition of design information quality from the user's perspective, although some authors have discussed AEC information quality. A purpose of defining and measuring design information quality is that improvements in processes, organization, and technology can be effective for improving design information. This leads to the research questions in Figure 11-1 and Figure 11-2.

PRQ 0:	**Can BIM objects reflecting building products improve design information in the AEC industry?**

Figure 11-1: A preliminary research question (PRQ) this research seeks to inform.

RQ 1:	**What types of design information problems do practitioners encounter when planning and executing construction work in the AEC industry?**
RQ 2:	**What criteria describe the quality of design information for designing, planning, and executing construction work in the AEC industry?**
RQ 3:	**Which observable phenomena can be utilized to assess the criteria of design information quality in the AEC industry?**

Figure 11-2: The research questions (RQ) this research seeks to inform.

The research questions describe the strategy to address the observed problem. The detailed steps and choices are accounted for in the research method and task in Section 13.

12. Research Quality

This section discusses the interaction of this research with the knowledge base. The knowledge base informed the methodological choices in the research to ensure research quality. The knowledge base is the scientific knowledge applied in the fields relevant to this research (such as BIM, construction management, information systems and SCOT). The knowledge base includes foundation (such as theories, frameworks, and instruments), methodology (such as data collection and analysis techniques), measures, and validation criteria accepted within the research fields (Hevner et al. 2004). The theoretical point of departure in Part II was included. This is as follows:

1. To discuss the foundation that informs the research scope and enables formulation of a research question (cf. Section 11).
2. To inform with theory the findings conducted in the research task (cf. Section 13).
3. To inform the methodological choices for data collection and analysis that provide research quality (cf. this section).

Design science from IS has primarily informed the methodological choices to deliver research quality. This section discusses the influence of design science on the thesis.

12.1 Paradigms

The interaction with the knowledge base was characterized by the search of what Kuhn (1970) refers to as a paradigm; that is, rules and standards for scientific practice. Kuhn describes his as follows:

> *Close historical investigation of a given specialty at a given time discloses a set of recurrent and quasi-standard illustrations of various theories in their conceptual, observational, and instrumental applications. These are the community's paradigms, revealed in its textbooks, lectures, and laboratory exercises. By studying them and by practicing with them, the members of the corresponding community learn their trade.*
> (Kuhn 1970)

Paradigms are not always explicit. They are learned through application, not by abstract or individual learning. Paradigms can also be described as shared beliefs of ontological (what is reality?), epistemological (what is knowledge?), and methodological (how can knowledge about reality be acquired?) assumptions (Guba and Lincoln 1994). According to Kuhn (1970) science can exist without paradigms. However, the pre-paradigm phase "is regularly marked by frequent and deep debates over legitimate methods, problems, and standards of solution."
In BIM, there is no explicit paradigm. Like information system research (see Section 9.1.2), BIM research combines different research traditions. Probably because BIM is a new field of research, it has not yet built a shared paradigm. Unlike shared theory in information systems research, BIM research does not yet discuss knowledge, theory, and methodology. Consequently, other fields can serve as a paradigmatic guide.

12.2 Science and Engineering

BIM does not provide guidance on how research quality is achieved. It is a multidisciplinary field, but a large share of research is conducted at technical universities and engineering schools. Thus, engineering research is an input to research quality. There is a profound difference between science and engineering. Coyle et al. (2007) described this difference as follows:

> *At its core, the scientist asks and answers the question 'why' whereas the engineer will ask and answer the question 'how.'*
>
> (Coyle et al. 2007)

Engineering is concerned with designing technologies to solve practical problems. Science is concerned with the pursuit and publication of scientific knowledge or truth. In essence, engineers apply science. Engineering science provides "the physical and mathematical basis to solve engineering problems" (Coyle et al. 2007). However, fields beyond physics and mathematics form the basis of engineering. Coyle et al. (2007), based on Rogers (1983), identified three principal reasons why engineering is different than science:

> *Firstly, there is a different purpose in what the scientist seeks to do, compared to what the engineer seeks to do. For engineering science the only criterion is that it be adequate for the underpinning or understanding of the relevant discipline, whereas science demands accuracy and precision to determine which of competing theories should be preferred.*
> *Secondly, the presuppositions for science are different than they are for engineering. Science is the discovery of knowledge and science presupposes that there is only one such set of laws to discover. Engineering presupposes that nature is capable of manipulation and modification.*
> *Thirdly, economic and social considerations play a much more important role in engineering than in science.*
>
> (Coyle et al. 2007)

Engineers practice in a variety of fields from designing concrete structures, to managing construction work, to simulating infrastructure. These are just a few examples from AEC. Engineering science designs the foundation, in the form of constructs, models, methods, and instantiations to help the engineer work. Thus, research in the engineering disciplines is closely related to design science in creating artifacts. Design science in information systems (cf. Section 9.2.1) creates artifacts related to information technology. Artifacts understood in the wide sense as suggested by Hevner et al. (2004) are constructs, models, methods and instantiations. The interest of the present study is models and methods to describe design information quality related to information technology, such as BIM. Hence, the outputs of this research and of design science are related. Consequently, design science was chosen as a field of reference for the methodological choices. Research quality will be discussed from the design science paradigm within information systems perspective.

12.3 Evaluation Criteria of the Research Quality

This research draws on qualitative methods. Scientific rigor is discussed in a qualitative tradition. In quantitative research, paradigm quality is expressed by scientific rigor. According to Lincoln and Guba (1986), rigor is made up of the four following factors:

- **Internal validity:** the research measures what it is supposed to measure (Joppe 2000).

- **External validity:** the findings can be generalized beyond the specific context of the research (Bryman 2004).
- **Reliability:** the results are consistent over time, and can be replicated or repeated by other researchers (Joppe 2000).
- **Objectivity:** the researcher's neutrality (Lincoln and Guba 1986).

The criteria of rigor cannot directly evaluate the quality of qualitative research due to the difference between quantitative and qualitative research (Lincoln and Guba 1986, Seale 1999, Golafshani 2003). Design science in information systems (cf. Section 9.2.1) and design science in engineering (cf. Section 12.2) are different from other paradigms. In both information systems (March and Smith 1995) and in engineering (Coyle et al. 2007), design science strives to create artifacts, rather than understand the world.

Design science served as a reference field for the methodology. Thus, criteria for achieving research quality in design science are discussed. Hevner et al. (2004) had seven guidelines for how design science contributes to theory (cf. Section 9.2.1). These guidelines concern the artifact (such as design as artifact, problem relevance, design evaluation), research (such as research contributions and rigor, design as search process), and communicating findings. The following subsections discuss these guidelines to identify criteria for research quality.

12.3.1 Criteria for the Artifact

Design science output is a useful artifact in practice. *Design as artifact* is the first guideline, since producing an artifact is a prerequisite for design science. Hevner et al. (2004) described an artifact as a construct, model, method, or instantiation.

This artifact needs to have *problem relevance* and importance for the business environment to which it is related. Relevance for the business environment is inherent in the nature of this research and has the observed problem (cf. Section 2) as a starting point, combined with a close interaction with the host company. Furthermore, a *design evaluation* of the artifact has to be conducted on utility, quality, and efficacy (Hevner et al. 2004). Evaluation requires practical implementation of the artifact in its environment. Artifact utility criteria are as follows:

- No adequate artifacts exist
- The artifact fits into the environment
- The artifact solves a problem.
  (Hevner et al. 2004)

Most importantly, the utility needs to be demonstrated.

To evaluate artifact quality, Hevner et al. (2004) proposed criteria including: functionality, completeness, consistency, accuracy, performance, reliability, usability, and organizational fit. They suggested identifying relevant criteria to evaluate a given artifact. This also depends on the nature of the artifact. The quality or usefulness of the research result is discussed in terms of implementability and usability. The evaluation criterion of efficacy is whether the artifact provides a desired output that is relevant and meaningful.

This research relates to Hevner et al.'s (2004) guideline criteria for the artifact; that is, design as an artifact, relevance, and utility, in the following way. The output is an artifact; that is, a model to describe design information quality and a method to measure it. The fact that no adequate applicable artifact could be identified was discussed and shown in the theoretical point of departure (cf. Section 7, 8 and 9.3). Throughout the entire study, there was a close interaction with the environment to ensure that the artifact has relevance to the environment. Ultimately, the artifact was implemented on a construction project and proved useable (cf. Section 13.5). Close interaction with the business environment and detailed studies of the problems (cf. Section 2 and

13.3) ensured that the problem was understood and addressed. Whether the problem can be considered solved has to be shown by subsequent research. A detailed discussion of utility can be found in Section 15.1.

Implementability, usability, and efficacy are tested by the implementation on a construction project (cf. Section 13.5) and discussed in detail (cf. Section 15). Implementability is provided and usability is achieved by supplying an extra resource to the project. Efficacy is shown for the case project, but has to be further investigated. These first three guidelines relate to the artifact (in this case, a model of design information quality), while the next criteria are related to research.

12.3.2 Criteria for the Research

Viable *research contribution*s in the design science paradigm are the artifact or contributions to the foundations or methodologies of design science. The artifact as a research contribution must address an unsolved problem either by extending the knowledge base or applying existing knowledge in new and innovative ways (Hevner et al. 2004). March and Smith (1995) argued that a contribution can also be significantly increased performance compared to an existing artifact. Performance improvement must be shown according to explicit criteria.

According to Hevner et al. (2004), *research rigor* is derived from rigorous construction and evaluation methods. This research draws on qualitative methods, so scientific rigor is used in a qualitative tradition. Lincoln and Guba (1986) suggested trustworthiness (equivalent to rigor in positivistic research) and authenticity as criteria. Trustworthiness consists of credibility (parallels internal validity), transferability (parallels external validity), dependability (parallels reliability), and confirmability (parallels objectivity).

In qualitative research, credibility depends on the ability and effort of the researcher (Golafshani 2003). *Credibility*, as described by Lincoln and Guba (1986), is achieved by lengthy and intensive studies of the phenomena of interest, including persistent observations of outstanding elements. Triangulation crosschecks findings by different sources and methods. Another important element is the search for what Popper (1963) called the falsifiability of science. This involves looking for cases that do not conform and exposing the research to impartial peers. The last element is to repeatedly check understanding of the phenomena with a sample of stakeholders.

Transferability, according to Lincoln and Guba (1986), is achieved by rich accounts and detailed narratives on the research phenomena. Bijker et al. (1987) argued for detailed descriptions of the situation being researched (cf. Section 10.3.2). A detailed description enables other researchers to make their own judgments about the possible transferability of the findings to another setting. Lincoln and Guba (1986) did note that “It is by no means clear how ‘thick’ a thick description needs to be.”

Dependability refers to the stability of the findings over time (Bowen 2005). It is parallel to *reliability* in quantitative research, which is concerned with whether the same results would be obtained if the same thing was observed twice. However, when studying social situations, no two are alike. Thus, dependability must account for the ever-changing context within which research is conducted (Trochim 2006). According to Trochim (2006), *confirmability* is the degree to which others can confirm the findings. Dependability and confirmability are the “establishment of an audit trail and the carrying out of an audit by a competent external, disinterested auditor” (Lincoln and Guba 1986).[25] External audits of the research design, method, and progress judges

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[25] A detailed description of the audit process can be seen in Lincoln and Guba (1985).

dependability, while judgment of the data and findings address confirmability. Bryman (2004) stated that external auditing is not popular due to the effort and time involved in an exhaustive audit. If an external audit is not viable, evaluation of dependability and conformability can be left to the reader.

Dependability can be shown by having acted in good faith (Bryman 2004) by describing choices and changes made during the research. Trochim (2006) suggested achieving confirmability by documenting the procedures of checking and rechecking, a documented process of another researcher as a “devil’s advocate” with respect to the results or describing negative instances that contradict prior observation. On the other hand, Brown (2005) suggested making the data available to inspection by the reader.

According to Lincoln and Guba (1986), *authenticity* is not defined in its parallel to quantitative research, but rather by unique requirements of the qualitative research paradigms. Authenticity consists of fairness, ontological authenticity, educative authenticity, catalytic authenticity, and tactical authenticity.

According to Lincoln and Guba (1986), *fairness* is about presenting a balanced view of all values and constructions. *Ontological authenticity* improves the individual’s or group’s conscious experience of the world, while *educative authenticity* increases appreciation of other individual’s or group’s conscious experience of the world, but does not necessarily mean agreement. *Catalytic authenticity* stimulates action based on inquiries and their analysis. *Tactical authenticity* empowers individuals or groups to take action (Lincoln and Guba 1986).

However, Seale (1999) criticized Lincoln and Guba, arguing that there is no fixed consensus on the desirability of particular goals. This makes political goals, such as fairness, sophistication, mutual understanding, and empowerment, problematic as research foundations. The research method and tasks are described in Section 13 to account for rigor.

Finally, returning to Hevner et al.’s (2004) guidelines, *design as a search process* refers to the iterative nature of design in pursuit of the best solution. Design alternatives are repeatedly created and tested.

The following accounts for how this research addressed the criteria for the research. The *research contribution* is a novel model and method for assessing design information quality in the AEC industry from the contractor’s perspective. Novelty is shown in the theoretical point of departure (cf. Sections 7, 8, and 9.3) and discussed in Section 16.1. Consequently, better performance cannot and has not been proven. Trustworthiness in terms of credibility, transferability, dependability, and confirmability is achieved in the following way.

Credibility is addressed by applying lengthy studies (until nothing new showed up); triangulation of methods (interviews and observations), sources (people and documentation), and different actors; and discussion of results with the participants and with focus groups of peers and practitioners (cf. Section 13). Transferability is achieved by documenting the research tasks in the research paper, which enables other scholars and practitioner to consider whether the findings are transferable to their situation. Dependability is accounted for by describing the choices and changes made during the research to show that this author has acted in good faith (cf. Section 13). Confirmability is difficult to document, since it is hard to show that another researcher has reached the same conclusions from the same data. The author of the present thesis has attempted to do this by providing the data that can be digitized to the interest audience on request, and it was available to the examination committee. Fairness is not considered relevant for this research, due to its political and controversial nature. Design as search is achieved by having the design evaluated several times by practitioners and peers.

12.3.3 Communication of the Findings

Research communication is important. It becomes particularly important to communicate research to the scientific and business communities when conducting research close to practice. Hevner et al. (2004) emphasized the need to communicate the results of design science to both technological audiences (to enable them to construct or implement the artifact) and management audiences (to enable them to purchase and use the artifact in their organizational context). This research was communicated through conferences, published papers, and meetings and workshops with managers and users in the case company.

12.3.4 Summary

Table 12-1summarizes Hevner et al.'s (2004) seven guidelines for conducting design science in IS and research quality criteria from the literature. The compliance in this research is described for each criterion; in other words, how the criterion was addressed in this research. The actual demonstration and discussion of compliance is conducted in the preceding and subsequent sections, which are referenced.

Hevner et al. (2004)'s guideline	Quality Criteria	Criteria Compliance
Design as an artifact	Output must contribute to the business environment.	The output of the research is a model that describes design information quality and a method to assess quality.
Problem relevance	Problem relevant to practice	Close interaction with the business environment and detailed studies of the problems (cf. Sections 2 and 13.3) to understand the observed problem.
Design evaluation	Utility, Quality and Efficacy of the artifact	Utility, quality and efficacy are tested by the implementation on a construction project (cf. Section 13.5) and discussed in detailed (cf. Section 15).
Research contributions	Unsolved problem or performance improvement	The contribution is due to novel an unsolved problem, discussed in the theoretical point of departure (cf. Sections 7, 8, and 9.3) and discussed in Section 16.1.
Research rigor	Credibility	Research method and tasks documented in Section 13. This research applies: lengthy studies, triangulation of methods, source and different actors, discussion of results with the participants and with focus groups of peers and practitioners.
	Transferability	Descriptions of the studies in the research papers.
	Dependability	Accounting for the choices and changes described in Section 13.
	Confirmability	The data is available on request.
Design as a search process	Iterative design	The design has been evaluated several times by practitioners and peers.
Communication of research	Communication to practice and science	The research was communicated through conferences, published papers and regular meetings to management and users in the case company.

Table 12-1: Hevner et al.'s (2004) **seven guidelines for design science, the identified quality criteria, and how this research complies with them.**

13. Research Tasks – Method and Findings

This research exists at the intersection between the social and the technical realms (cf. Section 10). It also exists between the business context within which the artifact operates (the model to describe and the method to assess design information quality) and the knowledge base (cf., Figure 13-1). The environment constitutes practitioners who work in companies within and organizations formed on AEC projects and the information technology they use. The knowledge base is the theoretical foundation that informs the research and to which it contributes. This base includes theories, frameworks, models, and constructs. The knowledge base also includes methodology for data collection, analysis techniques, and criteria for validation and evaluation (cf., Section 12, as well as Sections 7–10).
This section discusses research tasks, methods for addressing them, and how the tasks are related to each other. It also discusses how the tasks are informed by, and contribute to, the knowledge base, and how the research interacts with the environment. Figure 13-1 shows a schematic diagram of the research progress.

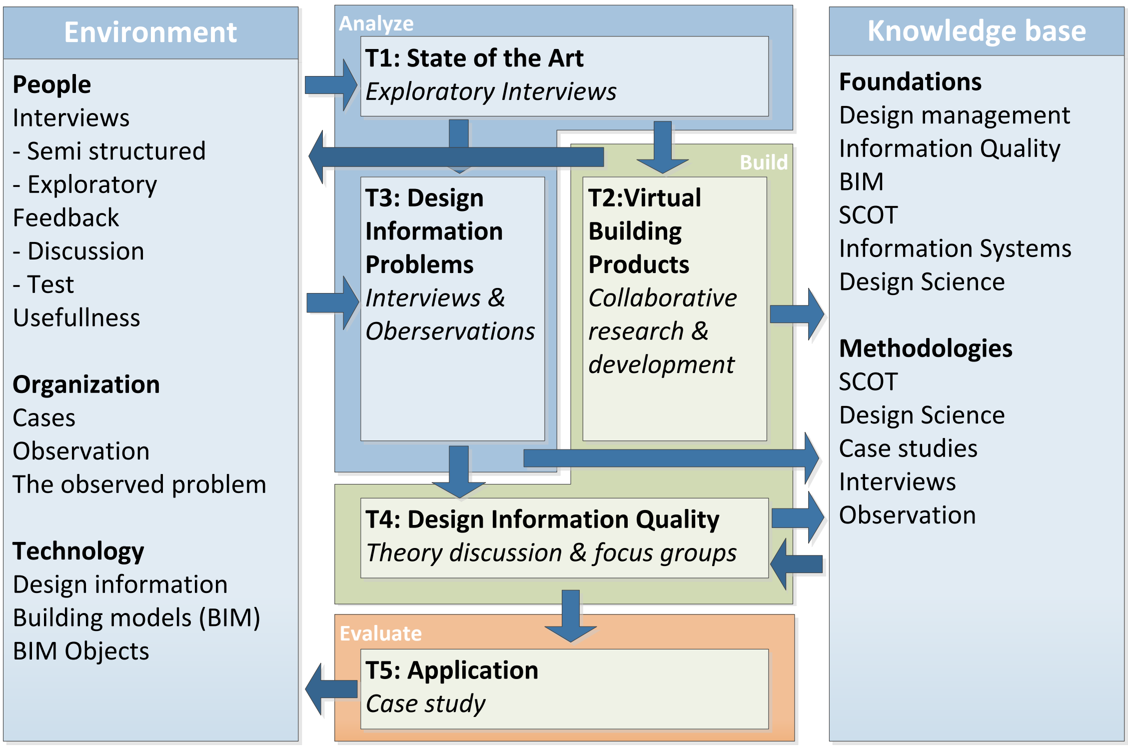


Figure 13-1: The research tasks of this thesis and their relationship, internally as well as to the environment and the knowledge base (adapted from Hevner et al. 2004).

Each research task in this section will address:

- What is researched – the purpose of the research task
- How the task is researched – the chosen methods
- Interaction with the knowledge base, development in practice, and other research tasks

Each research task was documented in a publishable paper that accounted for the detailed research methods and is attached to this thesis (cf., List of Papers Appended). This section places the tasks in a research context by highlighting the relationships between the tasks. The research tasks were divided into three phases (see Figure 13-1):

- The **analytical phase** worked to understand the nature of the problem, and constituted the highly exploratory research task 1 (T1): state of the art and the more specific T3: design information problems.
- The **build phase** involved designing potential solutions to the problems. This phase included T2: virtual building products and the design information quality framework in T4.
- In the **evaluation phase**, T5, the framework was applied to a construction project. Also, T2 included an evaluation.

The findings from each paper written during the PhD project are discussed below. This section briefly introduces the findings. Please refer to the full papers attached to this thesis for detailed findings.

13.1 T1: State of the Art

The first task was to investigate BIM's influence and use in practice. The primary purpose of this study was to discover the purposes for which BIM is used and how it is used in the AEC industry. This was done by interviewing individuals with experience working with BIM. The motivational question for this study was: "Why are people and organizations using BIM, and how are they using it?" The secondary purpose of this task was to supplement the review of research literature with a 2010 industry perspective. A detailed discussion of methods and findings is published in paper A.[26]

13.1.1 Method

The sample was architectural, engineering, and contracting companies in chosen countries. A total of 34 exploratory interviews (cf. Table 13-1) were conducted with 47 people.

	Denmark	Finland	Germany	Sweden	UK	USA	Sum
Architect	3	1	1	1	1	2	**9**
Engineer	4	2	3	1	2	0	**12**
Contractor	1	2	3	0	2	5	**13**
Sum	**8**	**5**	**7**	**2**	**5**	**7**	**34**

Table 13-1: The number of interviews by profession and by country.

The purpose was to describe how BIM was used and defined to inform the subsequent research. The research was highly exploratory, in that the research was purely empirical; the task drew entirely on the interviews. The research informed the body of knowledge by the practitioners' perspectives and applications of BIM. The environment, in the form of the case companies, benefited from insights into the practices of other companies.

13.1.2 Findings

The findings, which were introduced in Section 4, are briefly summarized here:

- The paper identified three uses of BIM in practice: building information model, building information modeling, and building information management. The idea be-

[26] Berard O (2012), State of the Art – An Investigation of Building Information Modeling. Working Paper. Not published.

hind building information management is that IT can help organize and distribute the information created on a construction project.
- BIM encouraged synchronizing workflows and information exchanges by agreeing on information delivery. This was supported by contracts that encouraged closer collaboration, such as design-build and IPD.
- Models were created for a specific purpose (such as producing drawings and coordinating design). It was difficult to use these models for purposes other than the original one. This meant that it was necessary to explicitly identify possible applications early on in the project.

13.2 T2: Virtual Building Products

The purpose of this task was to make necessary design information available to contractors. This was done by designing specific building-product BIM objects (such as virtual building products) and the process to create them. This research task was practical and considered information management, workflow synchronization, and models created from the previous task. The methods and findings of this research were first published in paper B,[27] and in a revised version as paper C.[28]

13.2.1 Method

The research method was based on a collaborative project with seven building-product manufacturers (see Table 13-2), where the researcher was actively involved in the development. The method included a series of workshops; follow-up interviews with the individual companies; an expert workshop and evaluation by practical implementation of the building products; and presentation and discussion of the solution to 10 subcontracting companies and two design companies.

Company	Product	Product/installation
Gyproc	Drywall, ceilings	Product
Rockwool	Insulation	Product
Kone	Elevators	Product, installation
Velfac	Windows, doors	Product
Cembrit	Façades	Product, installation
Expan	Prefab concrete	Product, installation
Tinglev Elementfabrik	Prefab concrete	Product, installation

Table 13-2: Building product manufacturers, by product, and whether they only sell the product or also install it.

The research informed the environment since the notion of virtual building products was developed by five of the participating building-product manufacturers. The task applied methods and models from the body of knowledge and contributed by evaluating such methods (that is, information delivery manuals; IDM; cf. Section 8.4.1).

The task informed this research by pointing it into a new direction. Virtual building products have the potential to deliver task-specific design information. Such products were a good business

[27] Berard O, Karlshoej J (2011). Information Delivery Manuals to Integrate Building Product Information Into Design. Proceedings of CIB W78 W102 2011, Sopia Antipolis, France, Paper 27.

[28] Berard O, Karlshoej J (2012). Information delivery manuals to integrate building product information into design. *Journal of Information Technology in Construction*, Vol. 17, pp. 63–74. www.itcon.org/2012/4.

opportunity, especially for building-product manufacturers. However, the researched approach was not viable for this research, because it was not possible to identify process and information needs at the necessary level of detail.

13.2.2 Findings

Papers on virtual building products suggest a superior way of managing design information for the contractor since the building-product manufacturer is in charge. The underlying concept was BIM objects (Revit families) that represented actual building products. These digital representations of the building products reflected its geometry. Furthermore, the virtual building products contained information that the contractor and the building-product manufacturer needed to perform a specific task. In this case, the task was to estimate the building of designs (the contractors' informational need) and provide design feedback (the building-product manufacturers' informational need). The purpose of the Revit families was to optimize communication between contractor and building-product manufacturer in terms of relevance, unambiguousness, and access to design information. For implementation, the contractor would encourage the designer to use the BIM objects when building the digital model. If this was not possible, the contractor could replace the generic BIM objects with virtual building products.

A test cased showed the practical implications of using these virtual building products. It specifically showed design errors that could be prevented by using BIM objects. An example was an elevator shaft that depended on the manufacturer. However, the criteria were an early design decision.

However, a major prerequisite for virtual building products was the contractor's ability to identify the information needs and work flow for a given task and relate them to the BIM object structure. This task might seem trivial, but it was the major challenge in this research. A workshop was conducted to discuss the information that was necessary for the bid for a design build project that would identify the work and information flow. While it was possible to identify a few general properties for the BIM objects, it was difficult to identify work and information flows with specific properties and how quantities should be presented if they were to be valid. These observations, congruent findings of other research (Hartmann et al. 2009, Fischer 2006), and further discussion with practitioners led to the realization that information in the AEC depended not only on tasks, but also on personal preference and project composition.

The idea was well received by contractors, subcontractors, and building-product manufacturers. Even purely geometrical coordination was beneficial, according to anecdotal evidence. However, another approach was required to fulfill the contractors' information needs. This was the point of origin of the next paper.

13.3 T3: Design Information Problems

The aim of this research was to explore information problems from the perspective of the companies planning and executing construction work, based on design information created by BIM. The purpose was to develop an in-depth understanding and model of the problems, which was the basis for discussing design information quality. The methods and findings of this research were documented in paper D.[29]

[29] Berard O, Fischer M (2012). Builders' Perceptions of Problems with Design Information from Building Information Modeling, Automation in Construction. Submitted.

13.3.1 Method

The research was conducted in the form of interviews with AEC industry practitioners and observations on a case study. Interviews were conducted in 11 organizations (six general contractors, three contract managers, and two subcontractors). A total of 16 people contributed. Design information problems were studied, rather than quality, because the notion of information quality was abstract for practitioners, while information problems were regularly encountered. This research drew heavily on the environment, through interviews. It was informed by the knowledge base in its methodological choice. In return, knowledge about practitioners' informational problems was created. This task provided the empirical basis for a framework of design information quality in T4.

13.3.2 Findings

The research for papers B and C led to the realization that information needs could not easily be defined. This was due to the concept that every construction project is unique. This concept of uniqueness from practitioners made it difficult to identify information requirements that could be coded into BIM objects.

The literature review for this research indicated that undesired outcomes such as building defects, budget overruns, schedule delays, and poor availability of relevant design information were related. Furthermore, studies of information quality in the AEC industry were very limited and did not include BIM. Existing literature did not render satisfactory answers, which meant that empirical research was needed. The findings of the previous tasks and the literature review led to the realization that the information problems encountered by practitioners must be better understood.

Contractors faced a variety of problems with design information, even when the design information was created with BIM methods. The interviews and case study led to the identification of 17 high-level issues, which were coded into nine types of design information problems (see Table 13-3).

Problem type	Description
Access	Effort required to access design information
Coordination	Level of coordination among different disciplines
Correctness	Extent of missing, incorrect, or outdated design information
Distribution	Routing and distribution of the design information
Format	Flexibility and conciseness of the medium
Handling	Effort to transform or update information regarding work tasks
Precision	Representation of actual working conditions in an accurate and unambiguous fashion
Relevance	Timing of information delivery
Volume	Number of documents, files, and other media

Table 13-3: Types of design information problems and brief description.

Due to its qualitative nature, this research did not quantify the problems. Instead, it introduced a model of design information problems for use in subsequent research. The output of this research was the subsequent research transformed into criteria for design information quality. However, the detailed framework of design information problems informed other research, which sought to understand problems in design information and BIM that contractors encountered, as well as research and developments to improve information management in the AEC industry.

13.4 T4: A Framework of Design Information Quality

In this task, the empirically identified design information problems were refined into criteria for design information quality. This was achieved by combining findings of other AEC research, as well as other fields in information quality, with the design information problems. The refinement led to a description of design information quality from the user's perspective. The purpose of this research task was to define, describe, and measure design information quality. The methods and findings of this research were documented in paper E.[30]

13.4.1 Method

The criteria of design information quality were identified based on empirical findings from T3 and the theory of design information quality from other fields. Based on design information problems and the criteria of design information quality, observable phenomena for each criterion were identified. These observable phenomena were classified into a five-point scale of levels of achievable practice (ranging from traditional to most innovative practice). The observable phenomena and the five-point scale were identified based on review of industry BIM literature (guidelines, standards, BIM plans, etc.)[31] and by three experts groups, BIM users (six people working with BIM at a contractor), BIM experts (four people from a BIM department), and BIM academics (three people from the BIM research group of DTU). The research task contributed to knowledge and practice with a framework of design information quality.

13.4.2 Findings

The core finding of this research task was eight criteria for design information quality (cf. Table 13-4). These criteria described design information quality from the user's perspective.

DIQ Criteria	Description
Relevance	The scope, sequence, and time-frame of the information delivery.
Consistency	The coordination of design information with respect to geometry, functional requirements, and compliance with standards and regulations.
Correctness	The extent of missing, incorrect, or outdated design information.
Precision	Accurate geometry and unambiguous requirements for the scope.

[30] Berard O (2012). A Framework for Assessing and Improving the Design Information Quality from Builders Perspective. Journal of Construction Engineering and Management, submitted.

[31] The following documents were consulted:

Common Design Workflow Checklist, 2008, FIATECH, Austin, TX, USA

AutoCodes Project: Phase 1, Proof-of-Concept Final Report, 2012, FIATECH, Austin, TX, USA

BIM Guide Series, 2007-2010, GSA, Washington, DC, USA

BIM Project Execution Planning Guide, 2010, The Pennsylvania State University, University Park, PA, USA

National Building Information Modeling Standard, 2007, National Institute of Building Sciences, Washington, DC, USA

BIM Management Plan Template, 2012, NATSPEC, Sydney, Australia

Model Progression Specification, 2012, Vico Software, Inc., Boulder, CO, USA

National Guidelines for Digital Modelling, 2009, Cooperative Research Centre for Construction Innovation, Brisbane, Australia

Integrated Project Delivery: A Guide, 2007, The American Institute of Architects California Council, Sacramento, CA, USA

AIA Document E202 - BIM Protocol Exhibit, 2008, The American Institute of Architects, Washington, DC, USA

The Business Value of BIM, 2009, McGraw-Hill Construction, New York, NY, USA

BIM Execution Plan, 2012, Indiana University, Bloomington, IN, USA

Availability	Effort to securely access current design information.
Distribution	Effort to manage, share, and route design information.
Flexibility	Effort to transform, extract, or update information for work tasks.
Amount of Information	The number of documents, files, and other media should be appropriate for the scope.

Table 13-4: Eight criteria of DIQ.

The next step was to measure design information quality. This is of interest to practice for such activities as comparing design information quality on different projects or measuring progress in design information quality and research (for example, to establish the relationship between design information quality and unintended outcomes). Ideally, design information quality was measured by quantitatively describing the difference between required design information and delivered design information. This measurement required design information consumers, such as contractors, subcontractors and designers, to specify information requirements, preferably in terms of objects and properties related to the BIM model, the sequence of information deliveries, and when information was needed. If these requirements could be defined and documented, then criteria such as relevance, consistency, precision, correctness, and distribution could be assessed automatically. Furthermore, availability, distribution, and amount of information could be measured by logging data from a project information-management system. Flexibility could also be assessed digitally.

However, it was evident (T2 and T3) that information requirements could not yet be identified in a general and purposeful way. Furthermore, the combined digital and paper information-management system does not allow for automated measures.

A suggested collaborative method (described below) to identify information requirements on AEC projects, based on the Last Planner method (Ballard 1999, Ballard 2000, Ballard and Howell 2003), did not provide the necessary level of detail. This method was applied in T5.

New means of assessing design information quality were identified upon realization of these limitations. Information quality and management depended heavily on procedures, technologies, and organizational settings that generated better information. Therefore, a procedure, technology, or organizational setting for each of the following criterion was identified to measure design information quality:

- **Relevance**: the procedure to establish information flow on the project. Evaluated by whether the receiver could identify and specify information requirements for conducting tasks, whether a continuous information flow could be established, and whether the sender could understand the receiver’s information requirements and act according to them.
- **Consistency**: the review and coordination procedure performed during and after the design phase.
- **Correctness**: the established procedure for correcting incorrect design information.
- **Precision**: the level of design information detail. This is evaluated by opposing the available and expected levels of detail.
- **Availability**: the “digital distance” to design information. Digital distance combines physical distance and the device used to access it. A paper drawing archive at the construction office is inferior to information available digitally in the work situation or contained on a mobile device.
- **Distribution**: the procedure to distribute design information to relevant receivers.
- **Flexibility**: the design information medium (such as paper documents, digital documents, BIM models).
- **Amount of information**: the negative effect (unmanageability) of information media quantity on design information quality.

Empirical research identified five observable phenomena for each criterion to measure the elements on the above list. These observable phenomena treated design information according to available practice (see Table 13-5). The scale included traditional, typical, advanced, best, and most innovative practice (Kam 2012). A description was presented for each criterion and practice type that scored the practice or technology of a project. Therefore, the combination of criteria, observable phenomena, and scale measured design information quality.
While the scale remains the same over time, the definition of the individual observable phenomena is adjusted regularly to suit the current practice. Technology and practice evolve. Technology that is a most-innovative practice today will become a best practice tomorrow and will be a traditional practice next week. In this way, measurement is corrected for progress in practice development, and the development of the organization is measured relative to the rest of the industries' practice.

Criterion	Traditional	Typical	Advanced	Best	Most innovative
Relevance	Contractor's informational needs are not identified; design information is sent at the end of each phase; sender is not able to fulfill specific informational needs.	Contractor's informational needs are not identified; design information is sent continuously; sender is not able to fulfill specific informational needs.	Contractor's informational needs are identified; design information is sent at the end of each phase; sender is able to fulfill specific informational needs.	Contractor's informational needs are identified; design information is sent continuously; sender is not able to fulfill specific informational needs.	Contractor's informational needs are identified; design information is sent continuously; sender is able to fulfill specific informational needs.
Consistency	Only coordinates, grids and naming conventions are shared.	Requirements are coordinated in a collaborative process.	Geometry is coordinated using software.	Building code requirements are coordinated using software.	All functional and behavioral requirements are coordinated using software.
Correctness	Design team is not available to provide correct information. (>4 weeks)	Request for information process must be followed (1-4 weeks)	Correct information is achieved by informal process. (5-7 days)	Correct information is achieved by fast-track process. (3-4 days)	Design team quickly provides correct information. (1-2 days)
Precision	Dimensions are sufficient for scope.	Level of detail is sufficient for scope.	Specifications are unambiguous.	BIM objects reflect production parts.	BIM objects reflect actual products.
Availability	Paper documents at the office.	Digital documents at the office.	Digital documents in a notebook.	Digital documents at the place of production.	Digital documents on a mobile device.
Distribution	Broadcast (information push).	Receiver chosen manually (information push).	Receiver chosen by role (information push).	Receiver subscription (information pull).	As specified by information requirements (information pull).

Flexibility	Documents.	Editable documents.	Geometric 3D models.	Building information models.	BIM according to information requirements.
Amount of information media	Documents.	Digital documents (not versioned).	Digital documents (versioned).	Multiple 3-D models and specifications.	Integrated 3-D models and specifications.

Table 13-5: Observable phenomena for each criteria to assess design information quality according to level of practice.

This framework was the core contribution of this thesis. However, the paper also suggested a method of identifying informational needs on a project-to-project basis in order to accommodate uniqueness. The method was an adjustment of on-phase scheduling in design as part of Last Planner (Ballard 1999, Ballard 2000, Ballard and Howell 2003). While design planning is traditionally rooted in drawings, the adjusted method was based on decomposition of building models into BIM objects. It was helpful to discuss informational requirements at the level of properties for the purpose of design planning. This method could eventually lead to automated assessment of design information quality. Until then, it has the potential to increase relevance, consistency, precision, correctness, and distribution by providing explicit expectations.
In addition to identifying informational requirement methods, the information delivery manual of the buildingSMART was suggested to capture informational requirements and the design structure matrix to put them in order. These project-based manuals and matrices inform design scheduling and are a form of agreement on project information flow. Furthermore, information delivery manuals can serve as input for generalized informational needs.
The framework was applied on a project to show applicability and usability. This was documented in detail by the research task that followed. Since the framework was the core output of this thesis, its usefulness, contribution to the knowledge base, and impact on practice is discussed in detail in Part IV.

13.5 T5: The Practical Application

The purpose of this task was to evaluate the applicability, usefulness, and fulfillment of the research question by implementing the design information quality framework. The methods and findings of this research were documented in paper F.[32]

13.5.1 Method

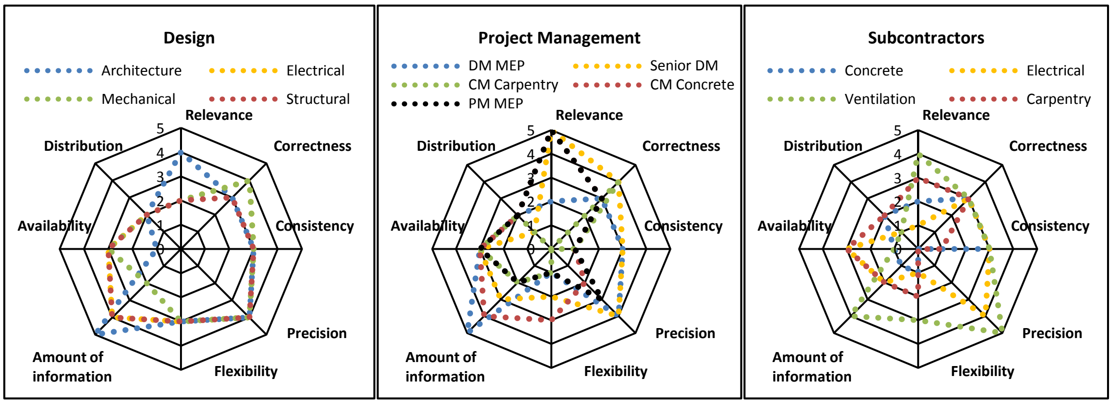
The practical application was evaluated by implementing the design information quality framework on a case project. The application had three phases. The case project started with an expert evaluation of the expected design information quality level. Detailed observations were made and BIM methods were implemented to improve design information quality. Finally, 13 interviews were conducted with four subcontractors, four designers, and five project managers.

13.5.2 Findings

Paper F discussed the direct implication of the framework to the construction project. It also discussed derived implications of the answers the framework can provide. Figure 13-2 shows the outcome of the interview survey. Project participants were asked to describe practices and technologies applied to the case and scored according to the framework. The discussion is left

[32] Berard O (2012). Assessment and Improvement of Design Information Quality on a Design-Build Project. Proceedings of CIB W78 2012, Beirut, Lebanon. Submitted.

to Paper F. In this section, the implications of the design information quality framework (model and method) are generally discussed.



CM = contract manager, DM = design manager, PM = project manager

Figure 13-2: Radar chart of the DIQ assessment according to role on the project.

The framework indicated DIQ problem areas in several ways.

- The difference between suppliers' and consumers' DIQ assessments indicated a problem. This was especially the case when the designer assumed a higher DIQ than the subcontractors did.
- An overall low score of a dimension indicated a common problem that needed to be addressed.
- A very heterogeneous assessment of a dimension indicated that clarification of established practices was needed, at the very least.

The DIQ framework enabled project participants to articulate and identify problems with the quality of design information. Furthermore, the framework measured the effect of implemented improvements.

13.6 The Interaction with the Environment

The nature of the PhD project entailed close interaction with practice, in the form of the host company. The host company's practices provided the problem, which was not solved by existing research and knowledge. Consequently, the purpose was to provide a solution to practice and contribute to the theoretical knowledge in the field.

This research was strongly based in a construction management environment. It was both physical and closely tied to its environment, which provided access to data to pursue the research tasks. The physical closeness provided many opportunities for observations and discussions that were related to the research tasks. The observations and discussions inspired this research and revealed areas to pursue in the research tasks. This became apparent in the observed problem described in Section 2.

This research was not only internally informed (within the host company), but also by insights into other companies' practices. T1 and T3 built on a variety of companies, while T2 included practitioner involvement from different companies. Finally, T5, due to the multi-organizational composition of construction projects, also included external companies.

Part IV – Discussion and Conclusion

This part discusses and summarizes the research findings. Firstly, the significance of this research is demonstrated by revisiting the research questions and stating the contribution to knowledge. Secondly, the utility, quality and efficacy in practical application of the artifact (in other words, the framework for design information quality) are evaluated. Finally, the impact on practice is predicted and further research is suggested.

14. Research Questions Revisited

This section revisits the preliminary research question and the other research questions to discuss how they have been addressed. The preliminary research question and the three research questions were derived in Section 11 and can be seen in Figure 11-1 and Figure 11-2. The research questions were:

PRQ 0: Can BIM objects reflecting building products improve design information in the AEC industry?
RQ 1: What types of design information problems do practitioners encounter when planning and executing construction work in the AEC industry?
RQ 2: What criteria describe the quality of design information for designing, planning, and executing construction work in the AEC industry?
RQ 3: Which observable phenomena can be utilized to assess the criteria of design information quality in the AEC industry?

The research questions were investigated through the research tasks, which were documented in the scientific papers. The interaction of research tasks is described in Section 13. Table 14-1 summarizes how each research question is informed by the scientific papers. This demonstrates the relevance of the papers and the relationship between the papers and the research question. Each paper represented one research task.

	Paper B & C	Paper D	Paper E	Paper F
PRQ 0	High			
RQ 1	Low	High		
RQ 2			High	
RQ 3			High	High

Table 14-1: Degree to which the research question was informed by the papers written.

The following section summarizes the findings or answers to each of the four research questions. More detailed descriptions of the findings emerged from section 13 and the scientific papers.

14.1 PRQ 0

Can BIM objects reflecting building products improve design information in the AEC industry?

This preliminary research question was pursued as the first research task of this thesis. Providing building-product specifics will provide better design information, in terms of more accurate geometry. Building-product specific BIM objects (in other words, virtual buildings products) even have the potential to provide timely and relevant design information to a higher degree then currently available, if information requirements can be identified. This research and the implementation of the virtual building products revealed two crucial problems.

- It is a prerequisite for the concept of virtual building products that information flows, workflows, and information requirements that are valid on multiple projects can be identified. However, this is not easily achieved because practitioners perce-

ive each AEC project as unique. It is not important whether projects are unique, since practitioners have treated them as if they are. Workflows and information flows will also be unique.
- Virtual building products provide geometrical accurate, timely, and relevant design information. However, these aspects are not the entire problem that contractors have with design information.

The realization of these problems, which are congruent with the research of other authors, led to a change in the research strategy, as described in Section 13.2.

14.2 RQ 1

What types of design information problems do practitioners encounter when planning and executing construction work in the AEC industry?

The observed problem, as described in Section 2 and the research for the virtual building products, indicated that contractors face a multitude of design information problems when planning and executing construction work. Nine types of design information problems were identified (cf. Section 13.3). *Access* describes the effort required to receive physical or digital design information. Problems related to *coordination* are caused by different design disciplines not aligning their designs with each other. Low *correctness* is the extent of missing, incorrect, or outdated design information. The *distribution* of design information is a problem because of the effort required to route and distribute information. Problems with the *format* are related to lack of flexibility and conciseness of the medium. *Handling* problems are the effort and time consumption of transforming (such as creating a materials schedule) or updating (such as when the design changes) design information regarding work tasks. The lack of *precision* is the degree to which actual working conditions are represented in an accurate and unambiguous fashion. *Relevance* is related to the timing of information delivery. Finally, the physical and digital volume that constitutes the number of documents, files, and other media can be problematic since it is difficult to maintain overview of the information.

14.3 RQ 2

What criteria describe the quality of design information for designing, planning, and executing construction work in the AEC industry?

RQ 1 provided the empirical basis for RQ 2. Eight criteria of design information quality, design planning, and execution of construction work from the contractor's perspective were identified. These criteria (cf. Section 13.4) are:

- **Relevance**: Scope, sequence and time frame of the information delivery
- **Consistency**: The coordination of design information, with respect to geometry, functional requirements, and compliances with standards and regulation.
- **Correctness**: Extent of missing, incorrect, or outdated design information.
- **Precision**: Accurate geometry and unambiguous requirements for the scope.
- **Availability**: Effort to securely access current design information.
- **Distribution**: Effort to manage, share, and route design information.
- **Flexibility**: Effort to transform, extract, or update information for work tasks.
- **Amount of Information**: The number of documents and files, and other media appropriate for the scope.

14.4 RQ 3

Which observable phenomena can be utilized to assess the criteria of design information quality in the AEC industry?

For each of the eight criteria of design information quality, five observable phenomena (see Table 14-2) were identified to score the criteria on a scale ranging from traditional practice to most innovative practice.

Criterion	Traditional	Typical	Advanced	Best	Most innovative
Relevance	Contractor's informational needs are not identified; design information is sent at the end of each phase; sender is not able to fulfill specific informational needs.	Contractor's informational needs are not identified; design information is sent continuously; sender is not able to fulfill specific informational needs.	Contractor's informational needs are identified; design information is sent at the end of each phase; sender is able to fulfill specific informational needs.	Contractor's informational needs are identified; design information is sent continuously; sender is not able to fulfill specific informational needs.	Contractor's informational needs are identified; design information is sent continuously; sender is able to fulfill specific informational needs.
Consistency	Only coordinates, grids, and naming conventions are shared.	Requirements are coordinated in a collaborative process.	Geometry is coordinated using software.	Building code requirements are coordinated using software.	All functional and behavioral requirements are coordinated using software.
Correctness	Design team is not available to provide correct information. (>4 weeks)	Request for information process must be followed. (1–4 weeks)	Correct information is achieved by informal process. (5–7 days)	Correct information is achieved by fast-track process. (3–4 days)	Design team quickly provides correct information. (1–2 days)
Precision	Dimensions are sufficient for scope.	Level of detail is sufficient for scope.	Specifications are unambiguous.	BIM objects reflect production parts.	BIM objects reflect actual products.
Availability	Paper documents at the office.	Digital documents at the office.	Digital documents in a notebook.	Digital documents at the place of production.	Digital documents on a mobile device.
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Flexibility	Documents.	Editable documents.	Geometric 3D models.	Building information models.	BIM according to information requirements.
Amount of information media	Documents.	Digital documents (not versioned).	Digital documents (versioned).	Multiple 3-D models and specifications.	Integrated 3-D models and specifications.

Table 14-2: Observable phenomena for each criterion to assess design information quality according to level of practice (note that this table is identical to Table 13-5).

15. Evaluation of the Artifact

The research seeks to contribute to practice and the knowledge base. To demonstrate the importance for practice, the artifact needs to be evaluated for its usefulness. This section accounts for the practical implications of the design information quality framework to demonstrate its usefulness in practice. The evaluation was based on Hevner et al.'s (2004) guideline of artifact evaluation, as described in Section 12.3.1. The utility, quality, and efficacy of the project were evaluated. The statement is based on the application of the framework from a detailed case study, as described (cf. Section 13.5).

15.1 Utility

According to Hevner et al. (2004), utility is evaluated by the following three criteria: No adequate artifact exists, the artifact fits into the environment, and the artifact solves a problem.

The practical point of departure (cf. Section 2), as well as T3 (cf. Section 13.3), showed that contractors regularly encounter problems with the quality of design information. They are aware of some of these design information problems, such as missing necessary design information and uncoordinated drawings, while others are accepted as conditions of doing business in the AEC industry, such as accessibility of drawings and the effort involved to extract the relevant information for a specific task from the pool of design information. Contractors have developed ad hoc and formalized methods to improve single criterion of design information quality, such as MEP systems coordination (Khanzode 2010).

Although contractors encounter design information problems, no model could be identified to describe and articulate design information quality from their perspective. There was also no means to measure and improve quality, from the contractor's perspective, that took BIM into account (cf. Section 7, 8 and 9.3). This is how the present study contributes. Therefore, even though a problem has to be solved, no adequate artifact exists in practice. Consequently, the design information quality framework developed in this research has the potential to solve an existing problem in practice; namely, the lack of design information quality.

The implementation of the framework on the case project showed that it can be applied in practice. The application also showed that the framework fitted into the specific environment of the specific project. Nevertheless, the degree to which the framework of design information quality fits in its environment (that is, the organization of a construction project) remains to be proven by further application on construction projects.

15.2 Quality

15.2.1 Implementability

The implementability of the framework answers the question: "What is the effort to implement the framework on a construction project?" Ease of implementation must be compared to the ability to provide meaningful answers, which is discussed in Section 15.3.

It became evident during this research that it is not easy to achieve an information requirements schedule. This and other research has shown that information is task-specific, and it is necessary to specify requirements to a supplier in order to achieve quality. It is an important premise for improving design information quality to enable the consumer (that is, the contractor) to formulate requirements for the information not only to content, but also to other criteria of design information quality. Consequently, a method of identifying information needs, referred to as design-phase planning, was suggested to supplement the framework provided by this research. This method has the potential to provide a detailed time schedule of informational deliveries. This schedule would be in a computer-readable format combined with a building model, and has the potential to allow automatic measurement of design information quality.

However, design-phase planning is not a prerequisite of the framework to make it operational, but a supplement. Hence when considering the implementability, the fact that design-phase planning is not a prerequisite to evaluate design information quality must be taken into account. Nonetheless, this is an important task to pursue, and the framework provided by this thesis is easily adjusted. Research T5 (cf. Section 13.5) has shown that design-phase scheduling entailed a significant change in the way of working, which meant that implementing it involved a great effort.

However, the actual framework is based on a questionnaire that makes it possible to score according to the currently available practice based on observable phenomenon. This provides an effective measurement, since the questionnaire can be conducted by a research assistant in 15 minutes. It is the author's belief that meaningful answers can be provided with a minimum of effort. This could be interviewing two designers and two subcontractors to contrast the perception of design information quality between these customer and supplier pairs. Hence, the framework can be implemented at minimal cost; specifically, a research assistant for a couple of days and four project participants for 15 minutes on a bimonthly basis (for example) to monitor design information quality progression.

15.2.2 Usability

As discussed in Section 12.3.1, usability is the ease of using and learning the framework. Discussions of usability must take into account both how data for the framework is collected as well as how the output is presented. That is, the usability of applying the framework and the usability of analyzing it.

It is part of the framework's method that data is collected by a research assistant and scored based on open answers to reduce respondent bias. However, the research assistant requires training and instruction to apply the framework in a meaningful way. This reduces usability, since the framework must be applied by external experts in order to improve the soundness of the results.

The results of the analysis are presented in a radar chart that provides a quick overview for the project manager. The radar chart allows in a graphical representation to identify criteria of low design information quality and criteria with divergent answers that need clarification. While the radar chart is a usable and applicable suggestion, more research is needed to discuss the graphical or numerical representation of the results.

While usability seems to be provided as a first proposition, this is also an area for subsequent improvement. Other methods of scoring, such as self-assessment or technology for scoring, need to be considered. The same is true for the representation of the results.

15.3 Efficacy

The efficacy is evaluated by whether the framework can provide relevant and meaningful answers. The application of the framework in the case study pointed to three major problem areas. Firstly, the divergence in the assessments of design information quality by subcontractors and designers in the fields of concrete and carpentry indicates that there is a problem that needs to be addressed. This is especially the case since designers assume higher design information quality than subcontractors. Secondly, an overall low scoring of a dimension indicates a common problem that needs to be addressed, as in the case of information distribution. Thirdly, a very heterogeneous assessment of a dimension indicates that clarification of established practices is needed. Thus, the application of the case framework on the project provided areas to discuss (cf. Section 13.5 and Paper F), which were recognized by the project manager when presenting it to them. Consequently, the framework points to potential problems. It is up to the project manager of the respective construction projects to evaluate the severity of the problems and the risk they constitute and engage preventive means. However, the framework can also suggest means to address the potential problems. This is achieved by identifying the desirable level of practice and the related observable phenomenon, which then can be implemented. Consequently, the framework provided meaningful answers for the case project.

16. Implications

16.1 Contribution to Knowledge

The purpose of this section is to explicitly claim contributions to the knowledge base. The contribution is made in the intersection between BIM research and construction management; specifically, design management in the AEC industry. This research makes three major contributions to the knowledge base.

1. **Understanding Design Information Problems**
   An in-depth understanding of the design information problems that contractors face when planning and executing construction work, even when BIM is used to create design information quality. Previous studies have not derived information problems from the user's perspective or studied them in the context of BIM.

2. **Criteria of Design Information Quality**
   The criteria of design information quality contribute to knowledge. Information quality criteria are not novel to either general or AEC research. However, deriving them from the perspective of consumer's informational problems is new. By establishing a new definition of AEC design information from the consumer's perspective, improvements are embedded in the problems encountered in practice.

3. **Assess Design Information Quality**
   The observable phenomena for each criterion create design information quality according to five levels of practice. Observable phenomena are a novel approach with which to assess design information quality in the AEC industry.

Together, these three contributions constitute the framework for assessing design information quality, which measures design information quality on construction using BIM.

In addition to the major contributions, this research suggests adjustments to well-established practice, such as design-phase planning and the information delivery manual, to accommodate design information quality.

16.2 Predicted Impact on Practice

This section discusses the predicted impact of the framework for assessing and improving design information quality on practice. This research not only contributes to knowledge, but also seeks to return practical results.
Although practitioners complain about low information quality, this is not a competitive factor and seems to be accepted as the price of doing business. Contracts, estimates, and schedules are based on this assumption of low information quality. The research can provide the means to articulate problems in design information quality, which can then be addressed. The study also provides a framework to conduct a risk analysis. Low design information quality entails problems in the respective criteria, such as the design being unclear or ambiguous, necessary information being unavailable, or the extraction of information being difficult. Consequently, the lack of quality in design information presumably adds risk to the project. Finally, measuring design information quality can track the effect of potential design information quality improvements, such as implementation of BIM methods and other process and technology improvements.

The model for describing design information quality and the method of measuring it are based on an integrated approach to design and planning (cf. Section 3) of construction work, such as design-build and IPD. The framework for design information quality assumes that BIM is used and is based on the contractor's perspective. The observable phenomena presume that the contractor and subcontractor are able to present their information requirements to the design team, which requires early involvement of the team. The model and method can regularly measure the design information quality on an integrated construction project.

However, the framework can be used in practice beyond this. The nine criteria provide a concept for viewing design information quality that is independent of project delivery form, project phase, technology choice, and actors' perspectives. Consequently, the criteria can evaluate design information quality and articulate problems. This could be used as a risk assessment before placing a bid. It also could be a quality assurance of the design information received for a design-bid-build project; or it can be used proactively to follow the progress of design information quality during a project. However, further research must investigate this. The observable phenomena do not seem directly applicable to these situations, since contractors' opportunities to specify informational requirements are limited in tender and design-bid-build projects. Altogether, this can put design information quality in focus and make it a competitive element in the relationship between designers, contractors, and subcontractors.

16.3 Further Research

The framework needs to mature by being applied to more cases. Further research can fine-tune the observable phenomena and scale, while quantitative research can prove validity and the generalizability of the criteria and observable phenomena.

Another interesting area of research would be output representation. This research suggests a radar chart to visualize the results. However further research could identify other ways to represent the output. The internal relation and prioritization of the criteria could provide weightings for the criteria. This could lead to a single value that represents the design information quality, which will ease statistical analysis of correlation between design information quality and outcomes of construction projects.

Furthermore, more studies into identification of information requirements of individual projects and their generalization can lead to automatic assessment of design information quality based on expected information. The framework of design information quality could have utility in other research areas within the AEC industry. The framework could help establish the relationship between design information quality and outcomes. A possible research question could be: How is design information quality related to schedule delays, building defects, or budget overruns?

16.4 Concluding Remarks

The framework can be subject to discussion in academia and practice. The different elements, such as criteria and the scoring scale, can be improved and validated. However, the framework provides a working means to measure design information quality. This framework has the potential to articulate design information quality and make it a competitive factor. Furthermore, it provides a measurement system to academia and practice that tracks the effect of potential improvements and studies the relationship between design information problems, and outcomes of construction work.

Part V – Papers

This part is constituted of the papers included in this thesis.

Appendix A Paper A: State of the Art – An Investigation of Building Information Modeling

State of the Art
An Investigation of Building Information Modeling

Ole Berard, MSc, Industrial PhD Student

October 2010

DTU Civil Engineering
Department of Civil Engineering

State of the Art
An Investigation of Building Information Modeling

Report [Nr.]
2010

By
Ole Berard, MSc, Industrial PhD Student

Cover photo: [Text]
Published by: Department of Civil Engineering, Brovej, Building 118, DK-2800 Kgs. Lyngby, Denmark
Request report from: www.byg.dtu.dk
ISSN: [0000-0000] (electronic version)
ISBN: [000-00-0000-000-0] (electronic version)

ISSN: [0000-0000] (printed version)
ISBN: [000-00-0000-000-0] (printed version)

Content

Abstract

This research investigates Building Information Modeling (BIM), which was conducted at the beginning of this PhD thesis work. This study focuses on the practical application of BIM and, first and foremost, on the reflections and considerations of practitioners in the architectural, engineering and construction industries with regard to the practical application of BIM. Thus, it is based on 34 qualitative interviews in 5 European countries and the USA. The study describes 3 meanings of the abbreviation: the digital model, the process of creating and using a digital model and the necessity to manage information. Three perspectives of BIM are the common denominator in the descriptions given by practitioners: the importance of collaboration, the focus on known workflows and the necessity of technology and process integration.

The study also discusses a struggle for market shares between designers and contractors. Furthermore, practical applications of BIM in contracting companies are highlighted because they are within the scope of the thesis. Perceived benefits, such as the opportunity to optimize the product and processes and an increased focus on quality and life cycle costs, and potential challenges, such as project managers and the difficulty in differentiation in the market for companies with expertise in BIM, that were identified by the interviews are discussed.

1 Introduction

This research was initially conducted between summer 2009 and winter 2010; although it has been revised in content and scope for publication as part of this PhD thesis in 2012, it represents the state of Building Information Modeling in 2009/2010.

- The author

Building Information Modeling (BIM) has been the subject of academic research, including research associated with its technologies, applications and potential, for many years. Industry organizations provide standards and guidelines for digitalization, such as the following:

- American Institute of Architects, USA
- Associated General Contractors, USA
- FIATECH International
- buildingSMART International

Public clients require BIM based on contracts and regulations, such as the following:

- General Service Administration, USA
- Statsbygg, Norway
- Senate Properties, Finland
- Danish Building and Property Agency

Textbooks on BIM are becoming increasingly popular, for example, the following:

- BIM Handbook, 2007, Chuck Eastman, Paul Teicholz, Rafael Sacks and Kathleen Liston, Wiley
- Big BIM little bim, 2008, Finith Jernigan, 4Site Press
- Building Information Modeling, 2009, Dana K. Smith and Michael Tardif, Wiley

However, a broad application of BIM in the architectural, engineering and construction (AEC) industry has still not been achieved.

The primary purpose of this study is to discover the purposes for which BIM is used and how it is used in the AEC industry by interviewing people who are experienced in working with BIM. The motivational question for this study is the following: Why are people and organizations using BIM, and how are they using it? The secondary purpose of this study is to supplement the review of the research literature available at the beginning of this PhD project with a current (i.e., 2010) industry perspective. The study provides new insights and thoughts on this PhD project to pursue, and it provided a network within the BIM community for later reference.

The study was conducted in two parts, namely a European study in summer 2009 and an American study in winter 2010. Some of the findings were presented at the annual Danish CAD and BIM users conference, bips Konferencen, in 2010, but the results remain unpublished.

During the interview a lot of data was collected, in the following, the most influential observations from the investigation of BIM on this PhD thesis will be presented. First, the method, which was highly exploratory, and the sample, will be presented. Then, the results, which depict how BIM is perceived by the interviewees, will be discussed in the later sections of the current paper.

2 Research Design

2.1 The Sample

Qualitative sampling is different, in terms of both purpose and technique, from quantitative methods. The purpose of quantitative methods is to make generalizations from the sample to the larger population. Thus, in quantitative research, statistical sampling is applied to achieve statistical significance. Qualitative methods provide in-depth knowledge to illuminate the questions under study. Thus, in qualitative research, purposeful sampling is applied, which allows the sample to be chosen based on selection criteria for information-rich cases that inform the research (Patton 1990).

Patton (1990) suggests 16 strategies for purposeful sampling, one of which is a combination of the others. One of these strategies is called intensity sampling, which encompasses *information-rich cases that manifest the phenomenon intensely*; that is, not seeking the extremely good or bad cases but rather the typical cases. Another strategy is criterion sampling, which entails *picking all cases that meet some criterion*. A combination of both strategies has been applied in this study. Within the field of study, typical examples rather than extreme cases were sought. However, within the field of design and construction management, BIM is an extreme case. Furthermore, a series of criteria were applied for sampling.

The survey population in this study is primarily composed of architects, engineers and contractors in the AEC industry. Because the focus of this thesis is contractors, they were preferred. The sample was geographically limited to Europe and the USA.

The geography was further limited to six countries chosen based on, first, prior knowledge of the BIM level (corporate and governmental), and, second, practical considerations such as language, time consumption and travel costs. The European countries chosen were Denmark, Finland, Germany, the Netherlands, Sweden and the United Kingdom. In the USA, the focus was on the San Francisco Bay Area, CA because this region is specifically advanced in BIM (McGraw-Hill 2009). The focus on the San Francisco Bay Area was supplemented by two companies in other regions of the USA because the opportunity arose.

From this list of countries and areas, a gross sample was compiled based on the following criteria:

- Membership in buildingSMART
- Membership in another BIM/IT initiative
- Presentations/papers at BIM conferences
- Scientific articles on BIM
- Professional articles on BIM
- Advertising material from BIM vendors
- Activity in BIM forums on the Internet

The gross sample was compiled to a net sample by analyzing the companies in terms of relevance to the objective of the survey, which resulted in a net sample of 63 companies (see Figure 1) that were contacted, 34 of which agreed to be interviewed (see Figure 2). Although 8 companies in the Netherlands were contacted, only 1 responded. Consequently, the Netherlands were excluded from the interviews.

	Denmark	Finland	Germany	Sweden	UK	USA	Sum
Architect	2	1	2	2	2	2	**15**
Engineer	5	2	4	2	3	1	**22**
Contractor	3	2	4	2	4	4	**24**
Sum	**10**	**5**	**10**	**6**	**9**	**7**	**63**

Figure 1. The net sample by profession and country.

	Denmark	Finland	Germany	Sweden	UK	USA	Sum
Architect	3	1	1	1	1	2	**9**
Engineer	4	2	3	1	2	0	**12**
Contractor	1	2	3	0	2	5	**13**
Sum	**8**	**5**	**7**	**2**	**5**	**7**	**34**

Figure 2. The actual number of interviews by professions and country.

2.2 The Research Method

The interviews were conducted as qualitative research interviews (Kvale 1996) with a semi-structured interview manual to guide the progress. The questions were open-ended to allow for the discovery of new topics during the interviews. All interviews were conducted by the author at the office of the interviewee and recorded digitally. After and during the interview, notes were written down. In addition to the digital records and the interview notes, material on BIM (e.g., slides, brochures and guidelines), either provided by the interviewee or publically accessible, comprised the data for the analysis. The analysis was conducted by grouping the data into categories. Categories were formed based on the interview manual and prior knowledge of the topic, but categories also emerged from the analyzed data.

3 Results and Discussion

When discussing BIM with professionals, three concepts emerge. BIM is associated with better *collaboration* between the stakeholders on a construction project, such as engineers, architects, contractors and the owner. A good collaboration is based on the synchronization of *processes*. Knowing who does what, when and how makes it possible to synchronize work internally and information flow externally. The last concept is *integration* of technology into the existing processes and systems. Technologies with which to perform BIM exist, but they have to be connected to share information. This chapter starts by discussing the flexibility of the notion of BIM through the different interpretations and meanings that the interviewees ascribed to the abbreviation. The key concepts of collaboration, processes and integration will be elaborated. The application of BIM by a contractor will be described. Finally, there is extensive anecdotal evidence of the benefits and challenges of digitalization in the AEC industry, and a few practioners have even discussed measuring them, which will be presented in the final section.

3.1 Definition of BIM

The abbreviation BIM, as well as the idea and artifact it implies, is not well established. Different actors have different perceptions of what it implies and even what the abbreviation represents. During the interviews, three trends emerged.

3.1.1 Building Information Model

BIM stands for Building Information Model; the center of this definition is the artifact, which is a three-dimensional, information-bearing and object-oriented model that is the digital representation of a construction. This building information model is the central data source for a construction project. There is not necessarily only *one* model; rather, it can be separate models created by different design disciplines or subcontractor trades, namely the so-called discipline models. BIM as an artifact will be referred to as the digital model below.

> ***"An integrated Building Information Model is a collection of interlinked domain models, sharing all the necessary information for design, construction and maintenance."***

Quotation 1 by [E07FI][1]

3.1.2 Building Information Modeling

BIM can also stand for Building Information Modeling. It is not the digital model that is important but rather the process of creating and applying it during the design, planning and execution of construction work. To achieve integration, the creation and application of digital models must be integrated with the existing working methods, which are achieved by adapting working methods

[1] The quotations in this section are marked by a structure code X##YY:
X can either be A for architect, C for contractor or E for engineer.
is a sequential number for each interview.
YY is the country code: DE for Germany, DK for Denmark, FI for Finland, SE for Sweden, UK for United Kingdom and US for the USA.

using the digital tools and models. Some US contractors refer to this as *virtual design and construction* to emphasize the process of building virtually first.

> ***"This [BIM] means to us the processes, not necessarily the actual output. But how can I make the prerequisites to implement these virtual opportunities, 3D models, to integrate with the existing operations."***

Quotation 2 by [C13DE]

3.1.3 Building Information Management

In the opinions of some interviewees, BIM refers to Building Information Management. The AEC industry depends heavily on information to design, plan and execute construction work. This information can either be connected to a digital model or exist independently. It is, however, of great importance to be in control of the information and the information flow. The central core of the information management perspective is having access to information, and knowing where to find the correct and necessary information is crucial.

3.2 A Power Struggle

The designs of architects and engineers have always served as a model that is an abstraction of reality that represents the final product (i.e., building) (Latour 1999). When the design is handed to the contractor, the model will be translated (i.e., build) into a physical artifact (i.e., a construction). Models have purposes, e.g., designers create design drawings to communicate the design for planning and procurements. When the models are handed from designers to contractors, there is a gap between the designer's vision (i.e., the design intent) and the contractor's comprehension of the product (i.e., the building to-be built). At best, the gap in information and communication is filled by the tacit knowledge of the contractors; at worst, it is filled by assumptions that negatively affect costs and quality. In traditional practice, shop drawings fill the gap, but they are not always created. Interviewees agree that working with digital models in 3D requires decisions regarding more design aspects to be made at an earlier stage simply because the technology does not allow for blank areas.

3.2.1 The Designer's Perspective

> ***"Suddenly it makes sense to return some of the deliveries [e.g. shop drawings] we have pushed away."***

Quotation 3 by [E27DK]

The level of detail of the information exchanged between design and construction is different depending on the market. BIM and digital models provide an opportunity for designers to model in greater detail, thereby gaining more influence on the configuration of a construction project. Furthermore, designers expect that contractors or the client are willing to pay for their extra effort. After all, they will reap the expected benefit of greater detail in the design information.

> ***"If they [the contractor] are [aware of the benefits in BIM]; it is more likely that we can sell the extra costs. When they can see that they are saving €100.000 through changing the installation sequence and paying us €20.000 for the model."***

Quotation 4 by [E10FI]

The business idea is that designers deliver a greater level of detail to ease the work of the contractor. BIM provides the opportunity for producing this business idea and also encourages it. Designers believe that BIM changes the design-making process, and more decisions have to be made earlier, which requires more time upfront. However, it will be repaid by a better design and building. It is an issue that the current fee structure does not encourage or support this reorganization.

> ***"In practice, this means that we have a higher burden in the draft design and a relief in the construction planning. Again, this shift is not supported by the HOAI[2].***

Quotation 5 by [A16DE]"

3.2.2 The Contractor's Perspective

Contractors have a different perspective on the division of the market by BIM. In the USA, there are traditionally three design phases: schematic design[3], design development[4] and construction drawings[5]. However, US contractors that were interviewed are beginning to use schematic design or design development as a basis and collaborate with their subcontractors by using their knowledge of building products and construction methods to create a detailed digital model of what is going to be built.

3.2.3 A Model Coordinator

BIM also gives rise to a new role, which is closely related to the information management perspective on BIM. Construction projects that use BIM produce many digital models, which are created by different disciplines and trades and at different stages in the construction process. To ensure the consistency of these digital models, they have to be coordinated and checked for compliance with requirements and regulations. Furthermore, it has to be assured that everybody has access to current and correct information, which is the basis for a new role, namely the model coordinator. This potentially influential role can be performed by either an existing actor or a new actor.

> ***"Model coordination and management is also a new service, like construction management."***

Quotation 6 by [E20DK]

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[2] HOAI: German fee specification for architects and engineers

[3] Schematic Design establishes the general scope, conceptual design, scale and relationships among the components of the project. Charles Levin Architects, 2012, http://www.charleslevinarchitects.com/

[4] Design development. In this phase, the architect expands upon the approved schematic design studies to develop more detailed drawings that illustrate other aspects of the proposed design. Charles Levin Architects, 2012, http://www.charleslevinarchitects.com/

[5] Construction drawings. Once the owner has approved the Design Development phase, the architect prepares detailed working drawings (formerly known as blueprints) and specifications, which the contractor will use to establish the actual construction cost and build the structure. Charles Levin Architects, 2012, http://www.charleslevinarchitects.com/

3.3 Collaboration

BIM is the basis of a power struggle between designers and contractors. At a conference, a designer claimed: *"Do not let the contractors take over BIM, they are using it to make more money out of you!"* Being in control of the project information through the use of BIM, digital models and information management is presumably effective in claims management. However, by modeling what has to be built, designers micro-manage contractors.

> ***"The biggest problem is the missing collaboration between the designer and the site, which is even worse in the building construction there is the group of Engineers and Architects that argue just because the contractor is stupid."***

Quotation 7 by [E18DE]

BIM is seen as a tool with which to achieve good collaboration. However, other companies use BIM primarily internally, which can be illustrated by a Finnish company that has spent many resources on the development of their internal processes. To them, it is important that they do not depend on the digital models of others. Consequently, they spend time and effort on every project to standardize design information that served as an input for their internal work. It is best if the architect provides a digital model, but, if the architect does not, the Finish company will create a model from the architect's drawings. Thus, the Finnish company can use BIM even if nobody else does.

> ***" We are also selling these tools [self developed BIM tools] to our competitors, but that is not big business, the big business is to support our internal processes. One of the dilemmas is that you cannot go too far ahead of your competition because then there is no market."***

Quotation 8 by [E07FI]

3.3.1 Better Collaboration

Good collaboration can be achieved through financial success in all parties. By this definition, the AEC industry often conducts bad collaborations. This tendency for bad collaboration is due to many factors: contracts that encourage sub-optimization; silos and fragmentation in the industry; and the fact that every project involves a unique combination of actors associated with the design, building and planning of a new building. Furthermore, there are large differences in backgrounds, beliefs and behaviors of the different actors, which may lead to irrational reasons for bad collaboration.

There are two major concepts associated with good collaboration. The first is the early involvement of different competencies in the development of new and innovative solutions at the right price and quality. The second is the notion that *"every project is a partnership"* built on strong, persistent alliances, which helps to break down silos and prevent sub-optimization.

3.3.2 The Model in the Middle

> ***"We mainly expect designers to do the modeling."***

Quotation 9 [C11FI]

The contractors interviewed stated that they wanted digital models for their projects, and many agree that digital models should be built by the designers. For the following reasons, a digital model is not always possible:

- No digital models are available because the designers are working in 2D.
- Digital models do not have the anticipated quality.
- Designers do not want to share the models because of legal and trust issues.

In the USA, legal issues are resolved by signing a waiver that exempts liability. Not having access to models leads contractors to model the buildings from 2D drawings, which is reasonable and enables quality assurance of the design. However, the development of sufficient building models requires an extra effort. This extra effort on the part of the contractor requires time and costs money, which could otherwise be used to improve the project. Furthermore, modeling from 2D drawiings is prone to errors because of the manual translation of drawings to models.

3.3.3 Collocation

> ***"The more people you involve early, the more profit you get later in the process."***

Quotation 10 by [E05SE]

The use of project offices or collocations is a well-known method of enhancing collaboration. The idea is to place at least the design team and the contractor, and possibly the client and subcontractors, in one office, which can be located at the construction site or in an office building. The assumption is that the physical proximity of these actors results in faster answers, better communication, early utilization of competencies, and faster decisions.

> ***"BIM only works if you work very closely together, even physically, that gives better understanding of each other's work."***

Quotation 11 by [E29DK]

Anecdotal evidence suggests that the effectiveness of collocation has been proven in many projects, but the problem is that it is not always practical. Large design companies involved in AEC projects do not necessarily design in the same city, or even the same country, in which the work is conducted. If the physical distance is too large, collocation becomes impossible. Instead, these projects are using information technology, such as video conferencing, instant messaging, social networking and project web sites, to support collaboration. They express that meeting in person is important to become acquainted, but it is not always necessary.

3.3.4 Contracts

It was mentioned earlier that contracts are an explanation of the lack of good collaboration in the AEC industry. Many agree that BIM can be effective in every contract if the project is seen as a partnership. However, the interviewees describe some contracts as more suitable for use with BMI than others, such as contracts where one actor brings together all risks, such as a design-build contract with the contractor as the lead. Even better are contracts based on shared risk and reward, collective decision making, trust, and early involvement of all competences, such as Integrated Project Delivery (IPD; (AIA 2007).

"Shared risk rather the blaming each other."

Quotation 12 by [C24UK]

3.4 Integration

"I believe: 'Whatever tool can be used; should be used', as long as the information gets back to the 'main model'."

Quotation 13 by [A06USA]

There is a multitude of software that supports the area of business for each individual participant in a construction project. For example, structural engineers use BIM authoring software and software for structural analysis, mechanical engineers simulate different aspects of their work with their specialized software, and contractors conduct their estimation and planning with their tools. Many of these tools do not work very well together. Consequently, either data have to be reentered manually, which is error-prone and laborious, or data loss due to the conversion between models has to be accepted.

Integration between software systems is not easily achieved, which is why the Finnish company (cf. Section 3.3) chose their tools, developed their own software and then integrated the commercial software in accordance with their work methodology.

3.4.1 Workflow Integration

The importance of integrating workflows is highlighted by the building information modeling perspective, where BIM is the process of creating and using the digital model in the design, planning and execution of construction work. In this perspective, the focus is on the integration of digital tools and models based on a defined process and workflow.

Many of the companies at which the interviewees worked, especially contractors, have BIM departments. These departments consist of internal consultants that identify the BIM tasks necessary for a construction project. Experts are creating and using BIM to support the construction project members, e.g., planners, estimators, project managers, and foremen. Thus, BIM is not an integrated part of the project's workflow and information flow.

Some companies are identifying workflows and processes associated with the integration of BIM, by which they can presumably define collaboration processes because shared interfaces can be defined and the information flow and digital deliveries can be agreed upon.

3.4.2 IFC

During the interviews, several technical solutions for achieving integration were discussed. One is the use of Industry Foundation Classes (IFCs) (ISO 2010), based on the idea that every piece of software implements IFCs as an exchange format. However, IFC implementation in a large amount of software is often insufficient. Most agree on the relevance of the IFC concept and that it is the most desirable means to achieve integration among the software and systems in the AEC industry.

"IFC is exactly what we want. The implementation of some software is not just as one would wish. We hope that there is more follow up to this."

Quotation 14 by [C15DE]

3.4.3 Software Platforms

An alternative to the IFCs is the use of software platforms. Platforms are packages of software from one vendor that use a common data format (e.g., Revit, AutoCAD, and Bentley) but represent the views of different disciplines on the model (e.g., AutoCAD MEP and Revit Structure). Platforms often have other applications built on top of them or direct links to other products of the same vendor. There is an expectation that software products from the same vendor work together more seamlessly.

> ***"The danger in using more software is that you spend more time on interoperability."***
>
> **Quotation 15 by [A30USA]**

3.4.4 DWG

DWG is a format used in Autodesk's software AutoCAD and is the de facto standard for the exchange of 2D drawings, but it can also be used for 3D geometry. It is seen as the lowest common denominator of integration because it is mostly the geometry that is exchanged, but it is also more reliable.

3.4.5 Concluding Remarks

Even though integration between software and interoperability are important issues for many companies, they are not easily achieved. A promising alternative to IFCs, platforms and DWG is to agree upon exchange formats and methods of exchange on a project basis, thereby enabling the identification of the best way to exchange data between the different software used by the participants to enable project integration to be achieved.

One vision of integration is a so-called model server. A model server is a place on the Internet where all information for a project is combined. The server handles transactions, user roles and rights, check in and out, and a change log. Every piece of software must be integrated with the model server and retrieve the data necessary for its use.

3.5 The Digital Contractor

> ***"Important to construction companies will be design management, health and safety, environmental, program scheduling, cost control, procurement, preconstruction, financial forecasting. BIM is the thing that affects all of those."***
>
> **Quotation 16 by [C23UK]**

The use of BIM by contractors is associated with becoming better and more efficient in planning and executing construction work. Through BIM, the contractor is in control of the information on a construction project, and BIM affects contractors in many business areas. In addition to becoming better at the existing business areas, BIM also provides a means by which contractors can become involved earlier, thereby enabling them to influence the construction cost and assist with consultations on constructible solutions.

3.5.1 Adding the '4th Dimension' of time

Traditionally, drawings have been made in two dimensions, namely width and length or height; however, design teams are now moving into the third dimension with 3D design and BIM to represent the final product. In physics, three dimensions describe a space, and time is sometimes referred to as the fourth dimension. Thus, '4D' implies that time is added to the 3D model. There are 3 major concepts in 4D modeling. The first is *phasing*, which refers to going through the major phases of the execution of construction work. The purpose of this concept is to show the client or collaborators how the structure is going to be built. The next is *scheduling*, which refers to the connection of the schedule at some level of detail to a model at a certain level of detail. The purpose is often to visualize the schedule and check its consistency; 4D modeling is seldom used as a proactive scheduling tool. The third concept is *sequencing,* where a certain area or building component is modeled in great detail and the sequence in which it is installed is visualized. This process helps the construction team to understand the construction process.

> ***"We have made 4D construction sequences from the Tekla model and compared it with pictures of the site to see what is missing and whether they are on the right stand, for both building shell and interior design."***

Quotation 17 by *[E14DE]*

4D modeling has several purposes; the main purpose is the involvement of different actors in the scheduling process by visualization of the schedule. In addition to involvement, it can illustrate the competency required to perform a job. It aids in identifying design issues. Furthermore, it is used to coordinate the work of subcontractors and find building system clashes in 4D designs, where two or more actors are working in the same place at the same time.
4D modeling is often related to the Line of Balance, an alternative scheduling method to the traditional Gant charts, based on locations and time.

> ***"4D is hype, a bit American. We have another way how to visualize scheduling and understand that. 4D can be a good tool to communicate with customers."***

Quotation 18 by *[C08FI]*

However, there are some major issues with 4D modeling. The first is that it is hard to keep it valid throughout the entire project due to its lack of integration into the existing working methodology. 4D modeling is often performed by a third person, who connects the schedule and 3D model. This task is performed once, but when the schedule and model change, it is difficult to keep it up to date. Another problem is that the model corresponds to the schedule because both are made for different purposes, which entails that the model has to be remodeled or at least customized.

> ***"We have modeling experience and we model these processes from the beginning. It is difficult to do that with external partners, as this model represents the production process."***

Quotation 19 by *[C12DE]*

Another aspect is the idea that the core competency of a contractor is to know how to build the building. This knowledge can be modeled in the digital model by adding the schedule or a time perspective, often referred to as 4D. In this way, BIM reflects and simulates the process of how to build the building.

3.5.2 Adding the '5th Dimension' of cost

> ***"The other [largest application] is QTO; that is easy and more and more common. At least in theory it is easy but in practice you have to know it very well. […] You have to know exactly what the content of the model is."***

Quotation 20 by [C08FI]

Adding the 5th dimension can mean many different things. It is often used to refer to the fact that the model is used for some type of estimation. The simplest implementation is quantity take off (QTO) from the digital model through the modeling tool or a specialized application and using it in the estimation process. QTO is rather simple and is commonly used. In this implementation, it is important to know what the quantities mean. As an example, the area of a window can refer to, e.g., the area of the opening, the frame, or the glass.

> ***"Model based estimates are 99.9% accurate to the old way. The estimating part is very decent; we have not finished a project yet."***

Quotation 21 by *[C32USA]*

The next step is to use the model for estimation. The quantities are not only extracted from the model but transferred to the estimation software to undergo a semi-automatic estimation process. This process is more difficult and requires being in control of the model and the estimation software. By automating parts of the estimation process, it becomes easier to conduct an economical analysis of a construction and becomes possible to analyze the costs of different designs. Not many companies have moved this far. The next step is to use the model to become even more in control of the economics by making predictions, developing payment plans and conducting spending analysis.

3.5.3 Constructability

Constructability is the degree to which a construction can be built. Furthermore, it refers to using the right building products and construction methods for the purpose. It is also related to the quality and consistency of the design information.

> ***"We have over 1000 holes in the building and only 20 – 40 the wrong place. The contractors really appreciate this, without 3D models it is a constant negotiation on site where to put the pipes."***

Quotation 22 by [E07FI]

Constructability can be ensured by 4D simulation. In addition, software for clash detection and building system coordination improves constructability. In clash detection, all trade and discipline models are loaded into software to check for clashes between building elements, and MEP systems are of special interest. Traditionally, 2D drawings have been overlaid on a light table with CAD software, but this manual process is error-prone. The clash detection software identifies problems in the design that would have remained hidden until construction.

Clash detection leaves the contractor with a dilemma. It has the potential to improve the project constructability and reduce errors found on site. However, clash detection provides quality assurance of the design information to a higher degree than usual. Because clash detection is a new concept, it entails extra work for the designer.

3.5.4 Getting Rid of Drawings?

Can we build without the drawings? The interviewees disagree on this question. The US AEC industry has a very strong requirement for *paper* drawings to be used as legal documents. Other interviewees hold the view that drawings do not necessarily have to be paper drawings but rather can be digital documents.

> ***"Nor do I understand the big win by not having drawings. It is important that the drawings are credible and have the correct version, or come from the most recent update of the model."***

Quotation 23 by [E05SE]

The digital document can be viewed on different devices, such as mobile devices or smart screens on site. The size of the screen is important for viewing a digital drawing on site, and it is argued that mobile phones are too small. A UK contractor used a tablet PC on site and learned that ordinary, fragile-looking tablets had a longer lifetime than the rugged tablets, as people take better care of fragile-looking things.

> ***"I believe there still will be drawings [in the future]. We will provide drawings for many years to come, but they gets fewer and fewer and more larger-scale, less details and sections."***

Quotation 24 by [E17DE]

Most interviewees agree that some "drawings" are necessary. However, when the level of detail in the model is sufficient, the contractor can take 2D views (i.e., drawings) from the model, which reduces the number of unnecessary drawings. These custom views of the model do not have to be 2D; videos might describe the intended assembly, and explosion models, for example, IKEA assembly guides, are are possible modalities with which to describe the design.

3.5.5 BIM on site

BIM and digital models are currently mostly used for design, planning, and estimation. Consequently, there seems to be a gap between design and planning and construction. However, a few companies are bringing the models on site in the form of viewers for notebooks, tablet PCs, smart boards or even specialists that help on site. It is seen as an issue that digital models are pushed on site without the project managers knowing what they can be used for. Furthermore, there is a discrepancy between what information is provided and what information is needed on the site.

> ***"Some projects have the models on the site, we unfortunately do not know how far the work on it. We lack, unfortunately, the feedback."***

Quotation 25 by [C15DE]

According to some, mostly US contractors, the next step is to give the models to superintendents, construction managers and foremen on site. Until this is established practice, it is necessary for this work to be guided by a specialist who is there to follow up on problems that might appear and to assure that the foremen are receiving the most out of building models. Companies that have tried this method are receiving positive feedback from the people involved.

> ***"We see that superintends once they grab a model really dig into it."***
>
> **Quotation 26 by [C31USA]**

Digital models can also encourage bidirectional communication. Planning and design information are brought on site, and, in return, control and status information can flow the other way. Tablet PCs are used to register, for example, the status, deficiencies, and errors associated with a project. Another option is to use a webcam or digital video camera to observe the progress of construction and to compare it to the schedule.

> ***"We have installed webcams and compare with the 4D model, the perspectives were put in the model and this is part of the controlling."***
>
> **Quotation 27 by [C13DE]**

3.6 Challenges, Benefits and Measurements

This section discusses the challenges met when using BIM, which are typically related to technology, processes and people. It includes a description of the benefits and, most importantly, a discussion of how the benefits can be measured.

3.6.1 Challenges

The immaturity of the software is a typical reason companies give for why they are not implementing BIM. Many of the companies visited do not accept software immaturity as an obstacle. These companies experience that by planning of information exchange and the development of software tools, interoperability issues can be overcome. A typical issue faced is the fact that models are built for a purpose, which is often to represent the design and to create drawings. When the models exist, it is difficult to change them to use them for other purposes. One challenge faced in the BIM process is that the contractor often does not know how to use the digital model. At some point in the project, the contractor discovers the digital model and wants to use it. The contractor then realizes that the level of detail and information contained in the digital model does not suit his/her purposes. Consequently, contractors need to determine the uses of digital models early in the project to avoid costly remodeling.

> ***"A model must be created for a purpose; at the end it is too late to change it."***
>
> **Quotation 28 by [E05SE]**

A few companies have invested heavily in development and implementation, but because BIM has become more popular, other companies claim to have the required competence and experience, and it is hard for the companies with experience to differentiate themselves.
The implementation of new technology in the construction sector has often been on a project-by project basis. Consequently, it is necessary to convince project managers to implement BIM. Top managers might see the benefits; however, project managers are solely evaluated based

on revenue, and the implementation of new technologies constitutes a risk. People working in construction are independent with regard to the way in which they work, without a predefined way of working, and they are trained to solve problems ad hoc because problems appear without warning and require immediate attention.

> ***"Project Management has some short-term goals. The key is to convince them."***
>
> **Quotation 29 by [E27DK]**

3.6.2 Benefits

One of the perceived benefits of BIM is that it is associated with a redistribution of the AEC market. With BIM, it might be easier to do somebody else's work. Designers move further into the contractors' planning, while contractors want to become involved in the project early to have influence on the design. Other ways to increase the market share include selling digital models or modeling abilities to other stakeholders and introducing a new role for model coordination.

> ***"It [BIM] also encourages optimization, because you can create variants with less effort. Predictive Analysis is very important because it leads to innovation and the only way we can maintain the market in high-wage countries."***
>
> **Quotation 30 by [C15DE]**

3.6.2.1 Optimization

By building virtually first, BIM provides the possibility of optimization. Optimization can refer to product optimization, process optimization in design or construction, or optimization of the collaboration. The digital model facilitates engineering analysis, such as energy, daylight and structural analysis, which optimizes design. 4D and 5D modeling allow the contractor to optimize the sequence and production method, as well as the product choice, based on informed decisions. Involving different groups in the early phase to discuss the digital model also encourages optimization. The standardization of spaces (e.g., bathrooms and offices) with interiors and dimensions (e.g., floor heights) can also streamline and optimize the construction process.

> ***"It [BIM] also encourages optimization, because you can create variants with less effort. Predictive Analysis is very important because it leads to innovation and the only way we can maintain the market in high-wage countries."***
>
> **Quotation 31 by *[E17DE]***

3.6.2.2 Quality

It is assumed that design and planning with BIM increases the quality of the final product (i.e., building) because BIM encourages quality assurance of the product before it is built, e.g., clash detection, and optimization (cf. Section 3.6.2.1) entails a better outcome. There is agreement that, while quality is increased and schedule time might be reduced, design and construction costs will not decrease and might even increase.

"Buildings will be delivered earlier and higher quality, but it do not think they will be cheaper."

Quotation 32 by *[A20UK]*

3.6.2.3 Life Cycle Cost

The focus of building clients has been on the initial investment and the cost of design and construction rather than on the cost of operation, because the client, operator and users of a building are not identical. Life cycle cost is discussed in the context of BIM, both because digital models enable an easier assessment of life cycle costs and because the increased involvement of different actors in the early phase of a project increases upfront costs with the expected benefit of decreased operation and maintenance costs. Developers that build to sell counteract the focus on life cycle costs because their interest is quick profit. Large private clients, such as US hospital operators, encourage life cycle cost assessment.

"The construction sector needs industrialization of lowering costs, not only construction costs but Life Cycle Costs."

Quotation 33 by *[A04SE]*

3.6.3 Measuring

Anecdotal evidence that BIM is beneficial because there are fewer building errors, fewer schedule delays and fewer cost overruns is strong. In addition, fewer building system conflicts, safety incidents, and change orders, as well as higher productivity, have been mentioned. However, the AEC industry has difficulties in quantifying this evidence, although some organizations have tried.

The most common way to quantify the evidence is to contrast identified clashes with the costs associated with software-based model coordination. Sometimes, the clashes are priced, although this pricing is very inaccurate because many clashes are solved on site. Another approach is to quantify the request for information and site-induced change orders and to compare those data to corresponding data from other projects. An interesting approach is to compare the increase in costs with the usual increase in cost for subcontractors. Another is to measure costs associated with certain tasks to determine how much is spent on data entry and quantity take off and then to compare them with costs associated with non-BIM projects. Modeling costs are typically between 0.1 and 0.5% of the project cost, and savings are at least 2 to 3 times that amount according to a German contractor and a US contractor.

"MEP package growth is typically around 20%, due to design changes and coordination errors. The actual growth was less than half of it."

Quotation 34 by *[E22UK]*

4 Conclusion

Three elements of this study have significantly influenced the further progress of this PhD thesis, namely the information management perspective of BIM, the notion of closer collaboration and, finally, the consideration that models have a purpose.

BIM is a digital model that provides a process with which to create designs and a way to manage project information. Although the information management perspective was commonly argued, the interviewees were not versed in its use to achieve information flow. BIM provides the opportunity to collect and aggregate information in a way that has not been possible before. The advantages and potential of the information management perspective extend beyond the individual project. BIM enables the development of information systems for construction that are equal to or even superior to systems in other professions. A prerequisite for its use is an increased awareness of the quality of information that the AEC industry captures in this information system.

Also noteworthy is that BIM provides a means to achieve closer collaboration, even though it seems to be contradicted by the struggle to increase market share. However, the higher quality of information and the final product require agreement on what the individual actors deliver to each other, which could be called a closer collaboration, but it could also be achieved by a contractual framework.

Models are created for a purpose, which is true not only for BIM but also for all types of abstractions of the world. It is difficult and sometimes impossible to use models for a purpose other than the one for which they were created. However, actors are not necessarily involved when digital models are created or, when involved, are not necessarily able to state their requirements for digital models.

These three observations are the basis for the further research conducted as part of the PhD thesis. The considerations of BIM described above provide a frame of reference for this PhD research.

Acknowledgements

The author would like to express his gratitude to all of the people and companies involved in this study. I would especially like to thank MT Hojgaard A/S for its support, the Ejnar and Meta Thorsens Foundation for funding this research and Peter Bo Olsen for his valuable feedback.

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Appendix A Questionnaire

Interview no:		Date:		Time:		Place:	

1) Company

Name:		Address:	
No. of Em-ployees:		Annual Turnover:	
Industry:		Project role:	

2) Interviewee:

Name:		E-mail:	
Position:		Tel. no.:	
Degree:		Age:	
4.1 Committee:			
Experience:			

Name:		E-mail:	
Position:		Tlf. no.:	
Degree:		Age:	
Committee:			
Experience:			

Name:		E-mail:	
Position:		Tel. no.:	
Degree:		Age:	
Committee:			
Experience:			

3) BIM status of companies

1) What does BIM mean to you?
    - How many projects is BIM used in?

2) IT strategy – Is BIM strategic and part of the business plan?

3) Commercial evaluation – Why use BIM?

4) In which areas do you use targeted software?
    - Modeling tools

5) BIM-Competencies
    - Investment in BIM – time and extent
    - Education/Competence level

6) Winnings/Focus areas

7) Presentation/Knowledge of the company

8) Future usage of BIM? (2 or 5 years)

BIM project

1) Project data

Name:		Construction price:	
Type (e.g., office or residence):		Area:	
Address:			
Collaborators:			
Contract form:			

2) BIM integration in the project (What has been done?)

3) Cooperation/exchange
    a. Internal (Who/When/What)
    b. External (Who/When/What)
    c. Coordination
    d. IFC or platform
    e. Data provided to the client

4) Consequences of BIM usage
    a. Constructional

    b. Non-technical (e.g., collaboration or satisfaction)

    c. Economical

    d. Why was BIM a success?

e. Competencies in the company (IT and constructional)

f. Reputation

5) Experiences
   a. What challenges have been met?

6) Necessary employee competencies

7) Model liability

8) What cooperation forms (contracts) are suitable for BIM?
   a. Closer cooperation

4) Personal Expectations

1) BIM direction in the IP's industry

2) Areas of focus

3) What is missing?

4) The biggest challenge

5) Opportunities/Visions

6) Largest usage

Appendix B Paper B – Information Delivery Manuals to Integrate Building Product Information into Design

INFORMATION DELIVERY MANUALS TO INTEGRATE BUILDING PRODUCT INFORMATION INTO DESIGN

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ABSTRACT

Despite continuing BIM progress, professionals in the AEC industry often lack the information they need to perform their work. Although this problem could be alleviated by information systems similar to those in other industries, companies struggle to model processes and information needs in the manner necessary to develop information systems that support digital collaboration, workflows, and information exchange. Processes for information systems can be described from four perspectives: task sequence, information need, organizational interaction, and required logic for the specific task. Traditional business process modeling languages often fail to completely cover all four perspectives. BuildingSMART has proposed Information Delivery Manuals (IDMs) to model and re-engineer processes that address the four perspectives through a collaborative methodology in order to standardize and implement them in information systems. BIM implies that objects are bearers of information and logic. The present study has three main aims: (1) to explore IDMs capability to capture all four perspectives, (2) to determine whether an IDM's collaborative methodology is valid for developing standardized processes, and (3) to ascertain whether IDM's business rules can support the development of information and logic-bearing BIM objects. The research is based on a case study of re-engineering the bidding process for a design-build project to integrate building product manufacturers, subcontractors and their knowledge about costs, construction methods, and products, with the intention of minimizing the time spent on non-value-adding tasks and reducing design errors.

Keywords: BIM, Building Products, Design Management, Information Delivery Manual.

1 INTRODUCTION

Building Information Modeling (BIM) has become increasingly popular in the architectural, engineering, and construction (AEC) industry. One of the perceived benefits of BIM is the organized and visual information it provides (McGraw-Hill 2009). However, it is costly for professionals due to information overload or the lack of high-value information (Tang et al. 2008) to access the information these professionals require. BIM constitutes a pool of digital information that could become an information system used to support design and construction processes. Manufacturing industries have acquired great benefits from implementing information systems to manage collaborative standardized processes and share information (Banker et al. 2006).

Information is related to processes because information needs are task- or process-specific (Eastman et al. 2010). Construction companies struggle to model and re-engineer processes in order to develop information systems for collaborative processes. One explanation for this is that products (that is, buildings) and organizations are perceived to be unique on every project, which necessitates the need to also adapt the processes and information (Hartmann, Fischer and Haymaker 2009). Becoming aware of information needs and making information requirements of other actors could help develop information systems, but also enhance collaboration in general.

1.1 Information Delivery Manual

The four following perspectives can be used to describe the processes for information systems: *functional* (i.e., business rules), *behavioral* (i.e., sequencing), *organizational* (i.e., actors), and *informational* (i.e., information elements) (Curtis, Kellner and Over 1992). According to a review by List and Korherr (2006) of seven business process modeling languages (including UML 2.0, IDEF3, and BPMN), all have shortcomings in terms of the organizational and informational perspective, whilst the functional and behavioral perspectives are generally well implemented.

The Information Delivery Manual (IDM) (NIBS 2007, ISO 2010a) is a business process modeling language that has been proposed to address the issues described above. The IDM is both a *product* to document information that needs to be exchanged to perform a task in a process, and also a *methodology* to model and re-engineer the process. As a *product*, the IDM extends Business Process Modeling Notation (BPMN) (White and Miers 2008). Unlike other methods for process modeling languages, the IDM does not focus on information products (that is, documents) but on in-depth descriptions of information elements (such as attributes) and their exchange through object-oriented models. The IDM consists of a process map (behavioral), narratives (organizational), exchange requirements (informational), and a narrative of business rules (functional) (Karlshoej 2011). The IDM as a *methodology* utilizes collaborative process re-engineering by involving multiple competencies (such as domain and software experts), as well as knowledge about BIM and the IDM to model or engineer cross-functional processes.

The IDM is part of the Information Exchange Framework for certifying IFC software (Wix and Karlshoej 2010). Other parts are Model View Definitions (MVD) (Hietanen 2008), which translate IDM into a document for software development, and Industry Foundation Classes (ISO 2010b), which provide the data structure. Although the three standards are closely affiliated, they are not inherently interconnected, either by ISO/AWI 16739 (ISO 2010a) or the US National BIM Standard (NBIMS) (NIBS 2007). On the contrary, the value of the IDM is beyond IFC certification and an IDM may become a legal agreement (NIBS 2007) between multiple parties for the purpose of enhancing their digital collaboration. The notion of *exchange objects* (Eastman et al. 2010, Aram et al. 2010) is used to explicitly decouple the IDM from IFC, rather than *exchange requirements*, as binding of data sets to a data structure should happen on the software development side (that is, MVD). BuildingSMART recently suggested keeping the IDM free of IFC bindings.

The IDM is gaining popularity in industry and research as a way of re-engineering and modeling processes and information flows. BuildingSMART lists 44 IDMs that are currently being developed (two of which are approved) (Karlshoej 2011). In the research literature, the IDM has been applied to pre-cast concrete (Jeong et al. 2009, Panushev et al. 2010), while suggestions have been made for implementation (Eastman et al. 2010) and improvement (Aram et al. 2010).

1.2 Knowledge in Digital Product Models

BIM implies that information is exchanged through product models consisting of CAD smart objects, so-called BIM objects (Ibrahim and Krawczyk 2003), digital components of parametric or static geometry, and information describing the state (for example, materials, dimensions) and behavior (for example, energy performance, price), that are aware of their relations to other objects, possibly implementing simple logic. In manufacturing industries (such as the automotive and aerospace industries), the integration of production knowledge in to object-oriented product models for the benefit of design and production is an established topic of research (Hvam 1999, Yang et al. 2008) and practice.

Fischer (2006) described how formalized construction knowledge can lead to self-aware *virtual elements* that “know” what affects their design and behavior and are able to react to it. Fischer argued that construction knowledge has not been formalized to a degree that supports this. Even though construction knowledge has not yet been formalized, atomic parts of it can be programmed into existing objects and provide value. Lee, Sacks and Eastman (2006) suggested that the building object behavior (BOB) notion describes knowledge embedded into BIM objects. The logic programming in BIM authoring tools provides a practicable point of origin with which to illustrate the potential, and it could be used to implement simple design and production rules. It is not yet possible to exchange BIM objects comprehensively through open standards (such as IFC), but Wei et al. (2010) did conduct research on this topic. This research relies on a commercial and proprietary format (Autodesk's Revit 2010 Families).

1.3 Background for the Case

The IDM claims to be a new methodology with which to model processes that address some shortcomings of other languages. An underlying assumption of the IDM is that processes must be standardized if they are to be implemented in information systems. Apart from the *behavioral*, *organizational*, and *informational* perspective, the IDM encourages description of constraints and logic in business rules, which relate to the feature of BIM object to implement simple logic. This is the motivation for the present study's evaluation of (1) the IDM's capability to capture task sequence, information needs, organizational interaction, and required logic; (2) whether the IDM's collaborative methodology is valid for developing standardized processes; and (3) whether business rules identified by the IDM can supplement the development of information and logic-bearing BIM objects. Since the IDM is task-specific, the evaluation is based on a case process: *the bidding process for a design-build project*.

The influence on and inclusion of contractors into design increases in new contract forms (that is, design-build and Integrated Project Delivery (IPD) (AIA 2007)). This is important for contractors and building product manufacturers, since they can receive orders based on their expertise in building solutions. The bidding phase of design-build projects is short and pressurized since the output is a complete design including planning and cost. The focus in this phase is on construction costs; however, as sustainability becomes an issue, life cycle costs and product quality become increasingly important.

Errors induced by the design are a significant source of errors during construction (30 percent of all errors) and maintenance (55 percent), many of which are caused by a lack of knowledge (44 percent), information (18 percent), or motivation (35 percent) (Josephson and Hammarlund 1999).

Research and practice have shown that sub-contractors and manufacturers can contribute to the optimization of design and construction (Gil et al. 2001) through better options for client customization and enhanced ease of off-site manufacturing (Elliman and Orange 2003), review and verification of constructability (Arditi, Elhassan and Toklu 2002, Pocock et al. 2006), better cost control by choosing the right product and production method (Slaughter 1993), fewer design errors due to thorough feedback (Johansson and Granath 2010), and exhaustive product data from the supply chain. Nonetheless, the design and the construction of a building are currently clearly separated tasks (Vrijhoef and Koskela 2000). Although rework costs do not vary significantly among procurement methods and project types (Love 2002), there seems to be a causal link between the project costs and good collaboration of the design and construction team (Love, Mandal and Li 1999). New contracts, such as IPD, address this issue from an organizational perspective. The present study intends to address it from a behavioral perspective. This is the why re-engineered bidding process for a design-build project must *free up time*, *reduce design errors*, and *integrate* sub contractors and manufacturers with the design.

2 RESEARCH METHODOLOGY

In this research the researcher becomes actively involved by facilitating the social situation that is being researched; this is referred to as action research (Hartmann, Fischer and Haymaker 2009, Somekh 1995). This type of research makes it necessary to distinguish between research methodology and development methodology (that is, the IDM). Action research is pragmatic and feeds the findings directly back to the practitioners. The challenge of action research lies in the rigor of the data collection. Collection is impossible without prior knowledge and is based on qualitative methods (such as unstructured and semi-structured interviews, notes, analytical memos and observations, development documents, workshops and discussions) and constantly challenging and following up on the development process. The view of technology in this research is inspired by the social construction (Bijker 1995). Technology, particularly BIM, is shaped by the struggle of different social groups. BIM has a high degree of interpretative flexibility, since different social groups have different applications for it. Architects consider BIM as a tool for outstanding design, as contractors would like to improve their productivity. These different views are not necessarily contradictory, they just illustrate that the technology is not stable and that closure has not been reached. Design methodologies that include the social groups in the development of the technology reach stable technology at a faster pace.

3 THE DEVELOPMENT OF THE INFORMATION DELIVERY MANUAL

3.1 Development Methodology

The working group consists of a contractor (responsible for estimation, procurement, project management and design management), two BIM consultants, seven building product manufacturers (– responsible for knowledge about products, estimation and sales; see Table 1), a software vendor (construction estimation), and the Technical University of Denmark (DTU – IDM expertise and academic monitoring). The manufacturers are categorized by terms from Supply Chain Management theory: *Made to Stock* (MTS) for off-the-shelf products (e.g., drywall), *Made to Order* (MTO) for products manufactured on order (e.g., windows), and *Engineered to Order* (ETO) for products that involve design (e.g., prefabricated concrete).

Table 1: Building product manufacturers, products by production category, and whether they just sell the product or also install it (service).

Production Category	Company	Product	Service/Product
MTS	Drywall Inc.	Drywall, ceilings	Product
MTS	Energy Efficiency Corp.	Insulation	Product
MTO	Up and Down Ltd.	Elevators	Product, Service
MTO	Clear View LLC.	Windows, doors	Product
MTO	Outer Shell Corp.	Façades	Product, Service
ETO	Light Concrete Inc.	Prefab Concrete	Product, Service
ETO	PreFab Ltd.	Prefab Concrete	Product, Service

Twelve manufacturers were invited to the initial workshop, six of which accepted (one joined later because of expertise in BIM). Invitation criteria included the variety of building products and production categories, avoiding competition, good collaboration with the contractor, and evaluation of their innovativeness. Based on a self-assessment by the manufacturer [1] of BIM needs (see Figure 1), the contractor and the individual manufacturers choose the products, attributes (see Section 3.3), and knowledge to be developed as BIM objects [2] (i.e., Autodesk Revit 2010 Families). The focus was on simple geometry, only necessary attributes, and simple rules to solve known design issues. Quality assurance of the BIM objects took place at DTU BIMlab where the BIM objects were used in software for different purposes [4]. The process was analyzed and modeled [5] collaboratively by an expert committee (see Figure 2) and a sub-group of the working group, and then validated [6] through a test case and follow-up interviews.

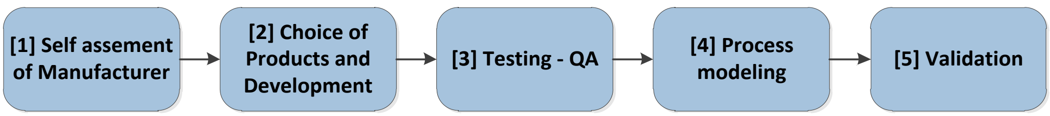

Figure 1: Schematic representation of the development process

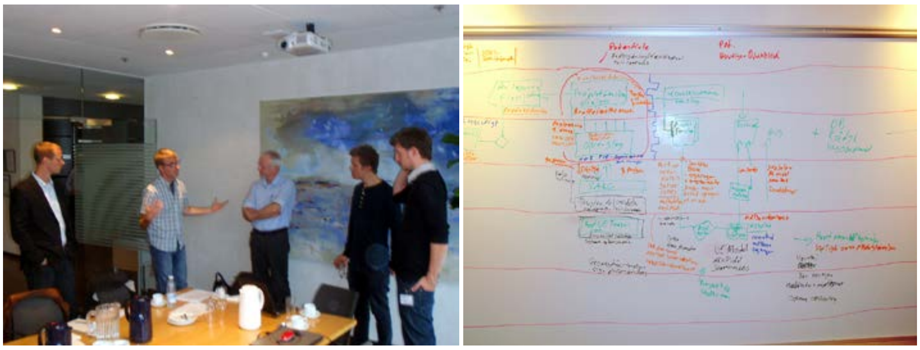
Figure 2: The expert group workshop

3.2 The Business Process

The existing process is typically sequential – starting with *design*, then *procurement*, and finally *compiling* the documents – with little opportunity for feedback between the main sequences. The *design* stage is more agile and runs in iterations that are not necessarily synchronized. Two main loops have been identified: the *program requirements* (placement of the building, aesthetic design, and performance requirements) and the *conceptual design* (the structural system, main routes for MEP, and choice of products and materials). The process is a compact version of the design and procurement of a traditional project.

During design, the estimator keeps track of the costs (two or three complete estimates). Before placing the bid, the prices needed to be covered by subcontractors or manufacturers. Communication is increasingly unstructured (for example, telephone conversations, emails, and file sharing). Designers lack knowledge about cost and constructability and want feedback on multiple design alternatives. Sub-contractors and manufacturers are rarely invited into the design, but often based on personal preferences and experiences or through the sales function of the manufacturer. Engineered-to-Order companies are more likely to be part of the design process, but not necessarily at the bidding stage. When Made-to-Order companies are involved, they often have to spend time adjusting products or design with each other. Involvement of Made-to-Stock products is limited to a quantity take-off.

For *procurement*, the sub-contractors and manufacturers receive a closed design without the opportunity or incentive to change it. In this context, their main challenge is the effort spent on information management (*"Sometimes we get 80 drawings; how do we find the right one?"*) and quantity take-off (*"Mostly we cannot even get a DWG drawing, which is easier to take measures from!"*). The output is a bid, including a specification of the costs and products. The last sequence is *"the time where the project manager does not sleep"*, compiling documents, prices, and presentation into a bidding document.

The improved process (see Figure 2), which integrates sub-contractors and manufacturers, can lead to a more cost-efficient design with fewer design errors. This has been shown in the literature and in practice, and has also been identified by participants. The improved process is built on *direct* participation, whereby knowledge is communicated by humans, and *indirect* participation, in which knowledge is communicated by computers through logic.

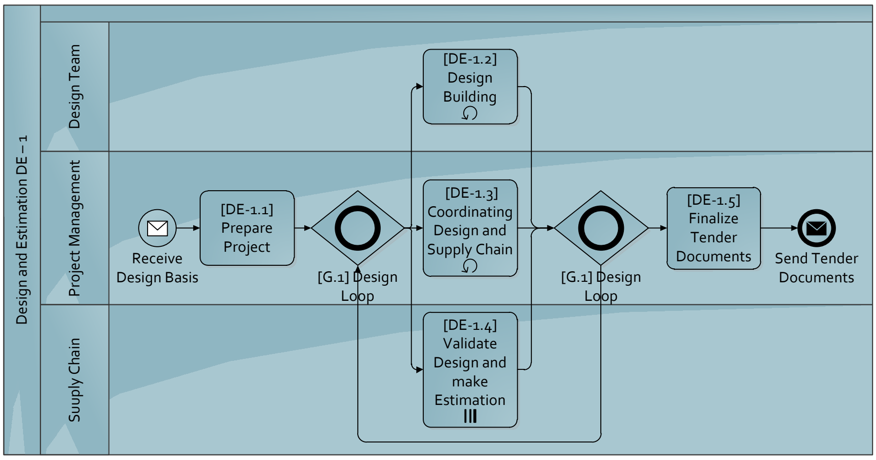

Figure 2: Overview of IDM process

The design team makes a product model of the conceptual design using product-specific objects that have been developed and maintained by the manufacturers, instead of using generic objects. These objects are loaded to a BIM authoring tool (see Figure 3) and equipped with simple rules (see Business Rules) to validate the design (for example, windows come in certain sizes); if the requirements are not fulfilled, the designer is notified. Information that a designer would previously have had to find by searching in a product information sheet or by contacting the manufacturer is integrated into the object. In this way, the manufacturer participates *indirectly* in the design. Afterwards, the product model is shared and can be accessed by the other designers, contractors, and manufacturers. In order to provide input that cannot be coded into the objects and for cost estimations, it is still necessary to involve the sub-contractors and manufacturers who participate *directly* in the design. Cost cannot be coded into the objects because product and labor costs depend on external factors, such as the volume of orders.

Ideally, project management can focus on coordination; forwarding the design to the sub-contractors and manufacturers and, vice versa, the design feedback and cost estimation to the design team. The product-specific objects also enable manufacturers to identify their part of the design and the IDM ensures that the necessary information is in the object (see Section 3.3). This enables the manufacturers to perform their tasks (estimation) with less effort spent on information management and quantity take-off. This frees up time that can be used to analyze design alternatives and provide valuable feedback to the design team beyond costs.

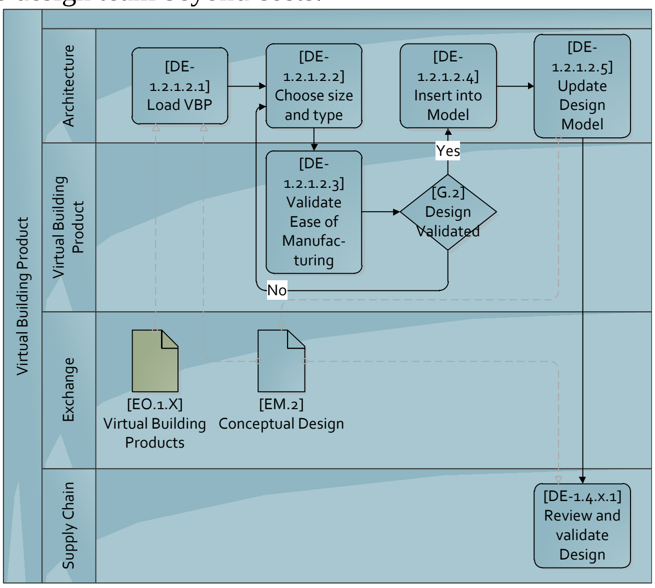

Figure 3: Working with the Virtual Building Product

3.3 The Exchange Objects

All types of products (ETO, MTO, and MTS) have the same basic information (see Table 2). ETO products that the manufacturer designs (that is, pre-cast concrete and lightweight pre-cast concrete) require additional information from the designers, such as structural system, load, and principal details. Traditionally, some of this information has not been communicated through CAD and requires additional documents, such as the structural load analysis.

Passenger elevators (MTO) are highly standardized and do not require a lot of geometrical and other information. More important are the business rules, to ensure that the elevator fits the shaft designed. For windows, doors, and façades (MTO) the space defines the requirements for the object (e.g., solar shading, noise reduction, safety, security, and fire). Manufacturers are also interested in the energy performance analysis to optimize the product choice. MTS products (insulation, drywall, ceiling, and floor) also need attributes that are derived from space (such as fire rating, noise reduction, robustness, and applicable surface requirements).

Table 2: Common information in all exchange objects.

Attribute	Data Type	Actor supplying	Documentation
Object Type	String	BPM	The type of building product
Manufacturer Name	String	BPM	Name of the manufacturing company
Model Number	String	BPM	Manufacturer's name/number of the product
Weight	Number	BPM	The lifting weight of the product (in kg)
U-Value	Number	BPM	Heat transfer coefficient of building element.
Links	hyperlink	BPM	Link to installation documentation
Material	Object	BPM	Name, quality, strength
Geometry	Numbers	BPM	Geometry that allows measures to be taken
Dimensions	Numbers	BPM	Dimensions that allows measures to be taken

3.4 The Business Rules

An important and obvious business rule is that objects can only have sizes and dimensions that are available for order. By way of example, two such business rules are explained in detail. The first issue is related to windows. According to the manufacturer and the contractor, the size of the opening (that is, a hole in a wall) must be the same size as the window including caulking. Normally a window has 12.5 mm caulking on each vertical side. However, when two windows or doors are adjacent the caulking must be 10 mm (see Figure 4).

The second example is passenger elevators. In addition to the lifting shaft, an elevator requires an overhead on top and an elevator pit in the bottom for the lift system and other technical installation. The size of these depends on the model and make of the elevator. According to the manufacturer, a common issue is that the chosen elevator does not fit the shaft, either in depth or width, or that there is not enough room for the pit or overhead. This can be costly if it is discovered after the concrete project is manufactured. Thus, one business rule for the elevator ensures that the width and height of the shaft is adjusted with the elevator design.

[BR-3] Window/Door Width

Type	Business Rule
Name	Window/Door Width
Documentation	It is mandatory that the width of an window/door is equal to the width of the opening subtracted 10 mm for each vertical side adjacent to another window/door and subtracted 12,5 mm for each vertical side not adjacent to a window/door.
Related to Concepts:	• [VBP-2.1.1] Window • [VBP-2.1.2] Glass Door

Figure 4: Example of a Business Rule

3.5 Validation

The IDM and the BIM objects were validated in three stages: a test project, follow-up discussions with participants in the working group, and interviews with a wider group of supply chain actors. The test case was based on a minor residential project designed by an architect. The BIM objects were loaded in the model after the design was finished to simulate real life conditions; it cannot be presumed that the architect will use the product-specific objects. This led to an unanticipated proof of the value: the elevator designed by the architect was too small (see Figure 5). The design was shared with the manufacturers in three formats: Revit, a Solibri Model Checker Information Take-Off highlighting the necessary attributes, and a DWF file for viewing purposes. The manufacturers were asked to review the design and give feedback on cost, design improvements, and specifications. Finally, the IDM was presented in an interview to a separate group of sub-contractors.

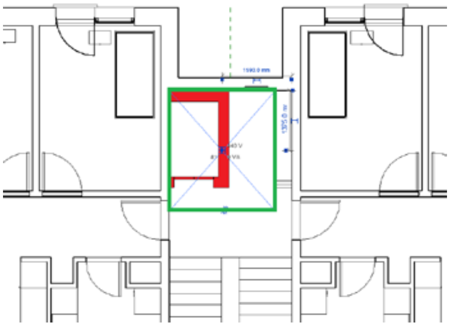

Figure 5: The elevator as designed (red) and as ordered (green)

4 RESULTS

The IDM builds on the BPMN to model process, as an established modeling language; it is able to capture the sequence and interdependence of tasks. Furthermore, the swim lanes (that is, actors or organization) address *who does what*, meaning that, supplemented with narratives, the organization can be well described. It can become trivial to describe the organizations and actors, since many roles in a construction project are well defined. References to definitions provided by other sources (such as OmniClass) could help.

IDM distinguishes itself from other process modeling languages in the way it addresses information. The Exchange Objects enable the detailed specification of information requirements to perform a task, rather than just addressing documents, the content of which might remain a black box in other approaches. This study used the IDM to describe information requirements to a proprietary format (Revit) and to define the *set of information* that needed to be exchanged independent of the *data structure*. The set of information could be exchanged in different *structures*, such as IFC, Revit files, and even in unstructured documents. To professionals, it is more important to communicate the necessary information (for example, "*I need to know the size of the window by Monday*") than whether that piece of information comes in an IFC model, a Revit file, an e-mail, or a phone conversation (although other considerations, such as traceability, could cause one to be preferred over the other). Mapping the information set to a data structure is the responsibility of the systems developer. This is why the IDM needs to be free of IFC bindings. The information, however, should be collected as data sets representing building products, to also support the way users think about information.

The IDM's business rules are a container for design knowledge, functionality, constraints, and transformation of information. The project used narratives to communicate business rules as suggested by the IDM. Narratives are ambiguous and can take a long time to capture the essence. A precise modeling language is beneficial for the brief communication of business rules, and it also ensures that the business rules are universally understood. The Production Rule Representation (PRR) of the Object Management Group (OMG 2009) provides a standard to express rules as syntax similar to programming languages (see Figure 6).

```
rule: Not Adjacent to Window or Door
ruleVariable:
    side : Side = window.Sides->any()
condition:
    side.IsVertical()
    and
        not side.IsAdjacentTo(typeOf(Window))
            or
        not side.IsAdjacentTo(typeOf(Wall))
action:
    window.Width -= 12.5 mm
```

Figure 6: Example of Production Rule Representation of the window width rule

IDM enforces the analysis and description of multiple perspectives of a process, and its context, which is necessary for developing an information system. To this end, IDM is a *check list* to ensure exhaustiveness. Unfortunately, this exhaustiveness is also the greatest disadvantage, since an IDM is not concise; most IDMs cover 50, 60, or more pages. This makes the methodology more suited than the product to make requirements to building product manufacturers and their BIM objects.

Construction project processes are highly flexible and, in today's practice, it is cumbersome to model a process in great detail in order to standardize it. Not only is the order of task execution different from project to project, but the interaction between organizations can also differ within a single project. A progressive window manufacturer may want to get involved in the design, while a more conservative one wants a list of his deliveries. The real world can turn out to be very different from the model, depending on the context, and it is counterproductive to trust a detailed model that has been made for the wrong purpose. Trying to map the sequence in these processes is a huge effort and it can be very time-consuming to collect the input from multiple sources. In addition, professionals can rarely recognize and accept the same processes, because they perform them differently. The challenge is to keep the processes general enough to suit different needs and specific enough to remain relevant. The result of a generic work-flow is not necessarily applicable in specific project. This is why modeling the process by tasks sequence has a low priority and must be high order and flexible; this also reduces the chances of getting lost in modeling process and *over-modeling*.

If it is not possible to standardize processes on construction projects, since they are unique and ever-changing, information systems need to support this. IDMs could contribute as a standardized way to communicate processes on construction projects. If construction projects documented their processes and information needs in a unified way, overtime processes could be combined and reused on projects and, finally, researchers could analyze processes for effectiveness and efficiency leading to improvement. In order to become functional on a project basis, IDMs lack the ability to address points in time. While they provide the sequence, they fail to address the actual date when a task needs to be performed and information needs to be exchanged. In the context of a project, the collaborative modeling and re-engineering of a workflow could define what information is needed to perform a workflow, ideally pulling the information from the previous actor. A simplified IDM could provide the methodology and the modeling language to make this work uniform.

Business rules can capture atomic parts of the workflows, which are so small and simple that they are part of many projects and so time-consuming that automation becomes relevant. An example is the business rule that provides the window size. It is a regular problem that is simple to implement in existing BIM software and it can prevent costly erroneous orders. Information needs can be so general that they are easily implemented as attributes into BIM objects. IDMs, on a project basis, can provide a lead and help identify business rules and attributes. However, to provide requirement specifications for companies developing BIM objects, the business rules and attributes must be compiled to a much simpler format to avoid overburdening the developers.

5 CONCLUSION

The Information Delivery Manual encourages consideration of information in terms of informational elements or objects and attributes rather than informational products (that is, documents), thereby enabling actors to analyze their information needs in detail. The collaborative method helps achieve multiple inputs for modeling the workflow, although this implies a great effort. The exhaustiveness of an IDM is also its greatest disadvantage; it is time-consuming to develop and communicate on projects. Rather than being a methodology to identify informational need on an industry basis, the IDM could be applied to identify processes and information needs in projects. Over time, the collection of these processes will enable professionals to choose processes. The main focus will not be to develop an information system, but to adjust the information exchange to suit the needs of the actors. In order to be applied to projects, the IDM must be able to handle time as points in time rather than sequences. Furthermore, the IDM needs a more concise terminology, a clear selection of detail level, and a strict de-selection of trivia. The IDM cannot be applied as requirement specifications for the development of BIM objects, because of its extent, but can form the basis upon which to compile the same.

This leads to the following suggestions related to the implementation of the IDM on a project basis: (1) Task sequence should be modeled at a high order; (2) the IDM must handle points in time; (3) The narrative description must be reduced by not requiring descriptions of well established roles; (4) the IDM should be completely independent of data structures; and (5) Business rules must be communicated unambiguously; for example, by a business rule modeling language such as PRR (OMG 2009).

ACKNOWLEDGMENTS

The authors would like to express their gratitude to all of the people and companies involved in this study. We would especially like to thank MT Højgaard for its support and for providing access to its supply chain; the Ejnar and Meta Thorsens Foundation for funding this research; and Rolf Büchmann-Slorup and Henning Roedel for their valuable feedback.

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Appendix C Paper C – Information Delivery Manuals to Integrate Building Product Information into Design

2011 CHARLES M. EASTMAN TOP PHD PAPER AWARD

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FOREWORD

The Architecture, Engineering, Construction and Operations (AECO) community is moving from a planning and documentation process that has been enabled manually by people (as a manual craft) to a digital process that supports automation, and to digital craftsmanship. The path of that transformation, in thinking, new processes and supporting technologies, has only begun. But as late starters, we have the advantage of learning from the other fields that have adopted digital representations, from obvious analogies such as aerospace, to more subtle ones, like the mass customization now practiced in digital dentistry.

An important dimension learned from these earlier developers is the central importance of process. Processes are the complement of a product, a project is the synergistic integration of both product – what a designer defines - and the process required to realize it. Digital models allow the integration of new automated processes in place of manual ones. These range from communicating a part of a design in a digital format, to checking of the design using rule-based systems, for example in terms of spatial conflicts, to describing an assembly process for the realization of the design – to a robot. Development of the criteria needed to define processes, not to just document them, but rather to re-define them and improve them, is a new and important capability that the following paper begins to address. What are the criteria needed to specify processes, to map them into implementable plans, the uniqueness of processes in construction, both in their individual steps and in their larger structure – these questions are well raised in the paper by Berard and Karlshoej. We need to develop lines of work that build upon one another that resolve one level and proceed to the next. For example, I hope the authors' work can be critiqued and improved, resulting in deeper understanding of the role of processes in the built environment.

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ITcon

www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

INFORMATION DELIVERY MANUALS TO INTEGRATE BUILDING PRODUCT INFORMATION INTO DESIGN

SUBMITTED: December 2011
PUBLISHED: May 2012 at http://www.itcon.org/2012/4
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SUMMARY: *Despite continuing BIM progress, professionals in the AEC industry often lack the information they need to perform their work. Although this problem could be alleviated by information systems similar to those in other industries, companies struggle to model processes and information needs in the manner necessary to develop information systems that support digital collaboration, workflows, and information exchange. Processes for information systems can be described from four perspectives: task sequence, information need, organizational interaction, and required logic for the specific task. Traditional business process modeling languages often fail to completely cover all four perspectives. BuildingSMART has proposed Information Delivery Manuals (IDMs) to model and re-engineer processes that address the four perspectives through a collaborative methodology in order to standardize and implement them in information systems. BIM implies that objects are bearers of information and logic. The present study has three main aims: (1) to explore IDMs capability to capture all four perspectives, (2) to determine whether an IDM's collaborative methodology is valid for developing standardized processes, and (3) to ascertain whether IDM's business rules can support the development of information and logic-bearing BIM objects. The research is based on a case study of re-engineering the bidding process for a design-build project to integrate building product manufacturers, subcontractors and their knowledge about costs, construction methods, and products, with the intention of minimizing the time spent on non-value-adding tasks and reducing design errors.*

KEYWORDS: *BIM, Building Products, Design Management, Information Delivery Manual.*

REFERENCE: *Ole Berard, Jan Karlshoej (2012) Information delivery manuals to integrate building product information into design, Journal of Information Technology in Construction (ITcon), Vol. 17, pg. 64-74, http://www.itcon.org/2012/4*

1. INTRODUCTION

Building Information Modeling (BIM) has become increasingly popular in the architectural, engineering, and construction (AEC) industry. One of the perceived benefits of BIM is the organized and visual information it provides (McGraw-Hill 2009). However, it is costly for professionals due to information overload or the lack of high-value information (Tang et al. 2008) to access the information these professionals require. BIM constitutes a pool of digital information that could become an information system used to support design and construction processes. Manufacturing industries have acquired great benefits from implementing information systems to manage collaborative standardized processes and share information (Banker et al. 2006).

Information is related to processes because information needs are task- or process-specific (Eastman et al. 2010). Construction companies struggle to model and re-engineer processes in order to develop information systems for collaborative processes. One explanation for this is that products (that is, buildings) and organizations are perceived to be unique on every project, which necessitates the need to also adapt the processes and information (Hartmann, Fischer and Haymaker 2009). Becoming aware of information needs and making information requirements of other actors could help develop information systems, but also enhance collaboration in general.

1.1 Information Delivery Manual

The four following perspectives can be used to describe business processes for information systems: *functional* (i.e., business rules), *behavioral* (i.e., sequencing), *organizational* (i.e., actors), and *informational* (i.e., information elements) (Curtis, Kellner and Over 1992). According to a review by List and Korherr (2006) of seven business process modeling languages (including UML 2.0, IDEF3, and BPMN), all have shortcomings in terms of the organizational and informational perspective, whilst the functional and behavioral perspectives are generally well implemented.

The Information Delivery Manual (IDM; ISO 2010a) is a business process modeling language that has been proposed to address the issues described above. The IDM is both a *product* to document information that needs to be exchanged to perform a task in a process, and also a *methodology* to model and re-engineer the process. As a *product,* the IDM extends Business Process Modeling Notation (BPMN) (White and Miers 2008). Unlike other methods for process modeling languages, the IDM does not focus on information products (that is, documents) but on in-depth descriptions of information elements (such as attributes) and their exchange through object-oriented models. The IDM consists of a process map (behavioral), narratives (organizational), exchange requirements (informational), and a narrative of business rules (functional) (Karlshoej 2011). The IDM as a *methodology* utilizes collaborative process re-engineering by involving multiple competencies (such as domain and software experts), as well as knowledge about BIM and the IDM to model or engineer cross-functional processes.

The IDM is part of the Information Exchange Framework for certifying IFC software (Wix and Karlshoej 2010). Other parts are Model View Definitions (MVD) (Hietanen 2008), which translate IDM into a document for software development, and Industry Foundation Classes (ISO 2010b), which provide the data structure. Although the three standards are closely affiliated, they are not inherently interconnected, either by ISO/AWI 16739 (ISO 2010a) or the US National BIM Standard (NBIMS) (NIBS 2007). On the contrary, the value of the IDM is beyond IFC certification and an IDM may become a legal agreement (NIBS 2007) between multiple parties for the purpose of enhancing their digital collaboration. The notion of *exchange objects* (Eastman et al. 2010, Aram et al. 2010) is used to explicitly decouple the IDM from IFC, rather than *exchange requirements,* as binding of data sets to a data structure should happen on the software development side (that is, MVD). BuildingSMART recently suggested keeping the IDM free of IFC bindings.

The IDM is gaining popularity in industry and research as a way of re-engineering and modeling processes and information flows. BuildingSMART lists 98 IDMs that are currently being developed (four of which are approved) (Karlshoej 2011). In the research literature, the IDM has been applied to pre-cast concrete (Jeong et al. 2009, Panushev et al. 2010), while suggestions have been made for implementation (Eastman et al. 2010) and improvement (Aram et al. 2010).

1.2 Knowledge in Digital Product Models

BIM implies that information is exchanged through product models consisting of CAD smart objects, so-called BIM objects (Ibrahim and Krawczyk 2003), digital components of parametric or static geometry, and information describing the state (for example, materials, dimensions) and behavior (for example, energy performance, price), that are aware of their relations to other objects, possibly implementing simple logic. In manufacturing industries (such as the automotive and aerospace industries), the integration of production knowledge in to object-oriented product models for the benefit of design and production is an established topic of research (Hvam 1999, Yang et al. 2008) and practice.

Fischer (2006) described how formalized construction knowledge can lead to self-aware *virtual elements* that "know" what affects their design and behavior and are able to react to it. Fischer argued that construction knowledge has not been formalized to a degree that supports this. Even though construction knowledge has not yet been formalized, atomic parts of it can be programmed into existing objects and provide value. Lee et al. (2006) suggested that the building object behavior (BOB) notion describes knowledge embedded into BIM objects. The logic programming in BIM authoring tools provides a practicable point of origin with which to illustrate the potential, and it could be used to implement simple design and production rules. It is not yet possible to exchange BIM objects comprehensively through open standards (such as IFC), but Wei et al. (2010) did conduct research on this topic. This research relies on a commercial and proprietary format (Autodesk's Revit 2010 Families).

1.3 Background for the Case

The IDM claims to be a new methodology with which to model processes that address some shortcomings of other languages. An underlying assumption of the IDM is that processes must be standardized if they are to be implemented in information systems. Apart from the *behavioral*, *organizational*, and *informational* perspective, the IDM encourages description of constraints and logic in business rules, which relate to the feature of BIM object to implement simple logic. This is the motivation for the present study's evaluation of (1) the IDM's capability to capture task sequence, information needs, organizational interaction, and required logic; (2) whether the IDM's collaborative methodology is valid for developing standardized processes; and (3) whether business rules identified by the IDM can supplement the development of information and logic-bearing BIM objects. Since the IDM is task-specific, the evaluation is based on a case process: *the bidding process for a design-build project*.

The influence on and inclusion of contractors into design increases in new contract forms (e.g. design-build and Integrated Project Delivery (IPD) (AIA 2007)). This is important for contractors and building product manufacturers, since they can receive orders based on their expertise in building solutions. The bidding phase of design-build projects is short and pressurized since the output is a complete design including planning and cost. The focus in this phase is on construction costs; however, as sustainability becomes an issue, life cycle costs and product quality become increasingly important.

Errors induced by the design are a significant source of errors during construction (30 percent of all errors) and maintenance (55 percent), many of which are caused by a lack of knowledge (44 percent), information (18 percent), or motivation (35 percent) (Josephson and Hammarlund 1999).

Research and practice have shown that sub-contractors and manufacturers can contribute to the optimization of design and construction (Gil et al. 2001) through better options for client customization and enhanced ease of off-site manufacturing (Elliman and Orange 2003), review and verification of constructability (Arditi et al. 2002, Pocock et al. 2006), better cost control by choosing the right product and production method (Slaughter 1993), fewer design errors due to thorough feedback (Johansson and Granath 2010), and exhaustive product data from the supply chain. Nonetheless, the design and the construction of a building are currently clearly separated tasks (Vrijhoef and Koskela 2000). Although rework costs do not vary significantly among procurement methods and project types (Love 2002), there seems to be a causal link between the project costs and good collaboration of the design and construction team (Love et al. 1999). New contracts, such as IPD, address this issue from an organizational perspective. The present study intends to address it from a behavioral perspective. This is the why re-engineered bidding process for a design-build project must *free up time*, *reduce design errors*, and *integrate* sub contractors and manufacturers with the design.

2. RESEARCH METHODOLOGY

In this research the researcher becomes actively involved by facilitating the social situation that is being researched; this is referred to as action research (Hartmann et al. 2009, Somekh 1995). This type of research makes it necessary to distinguish between research methodology and development methodology (that is, the IDM). Action research is pragmatic and feeds the findings directly back to the practitioners. The challenge of action research lies in the rigor of the data collection. This collection is impossible without prior knowledge and is based on qualitative methods (such as unstructured and semi-structured interviews, notes, analytical memos and observations, development documents, workshops and discussions) and constantly challenging and following up on the development process. The view of technology in this research is inspired by the social construction of technology (SCOT; Bijker 1995). Technology, particularly BIM, is shaped by the struggle of different social groups. BIM has a high degree of interpretative flexibility, since different social groups have different applications for it. Architects consider BIM as a tool for outstanding design, as contractors would like to improve their productivity. These different views are not necessarily contradictory, they just illustrate that the technology is not stable and that closure has not been reached. Design methodologies that include the social groups in the development of the technology reach stable technology at a faster pace according to SCOT.

3. THE DEVELOPMENT OF THE INFORMATION DELIVERY MANUAL

3.1 Development Methodology

The working group consists of a contractor (responsible for estimation, procurement, project management and design management), two BIM consultants, seven building product manufacturers (responsible for knowledge about products, estimation and sales; see Table 1), a software vendor (construction estimation), and the Technical University of Denmark (DTU – IDM expertise and academic monitoring). The manufacturers are categorized by terms from Supply Chain Management theory: *Made to Stock* (MTS) for off-the-shelf products (e.g., drywall), *Made to Order* (MTO) for products manufactured on order (e.g., windows), and *Engineered to Order* (ETO) for products that involve design (e.g., prefabricated concrete).

TABLE 1: Building product manufacturers, products by production category, and whether they just sell the product or also install it (service).

Production Category	Company	Product	Service/Product
MTS	Drywall Inc.	Drywall, ceilings	Product
MTS	Energy Efficiency Corp.	Insulation	Product
MTO	Up and Down Ltd.	Elevators	Product, Service
MTO	Clear View LLC.	Windows, doors	Product
MTO	Outer Shell Corp.	Façades	Product, Service
ETO	Light Concrete Inc.	Prefab Concrete	Product, Service
ETO	PreFab Ltd.	Prefab Concrete	Product, Service

Twelve manufacturers were invited to the initial workshop, six of which accepted (one joined later because of expertise in BIM). Invitation criteria included the variety of building products and production categories, avoiding competition, good collaboration with the contractor, and evaluation of their innovativeness. Based on a self-assessment by the manufacturer [1] of BIM needs (see Fig. 1), the contractor and the individual manufacturers choose the products, attributes (see Section 3.3), and knowledge to be developed as BIM objects [2] (i.e., Autodesk Revit 2010 Families). The focus was on simple geometry, only necessary attributes, and simple rules to solve known design issues. Quality assurance of the BIM objects took place at the universities BIM laboratory (DTU BIMlab) where the BIM objects were used in software for different purposes [4]. The process was analyzed and modeled [5] collaboratively by an expert committee (see Fig. 2) and a sub-group of the working group, and then validated [6] through a test case and follow-up interviews.

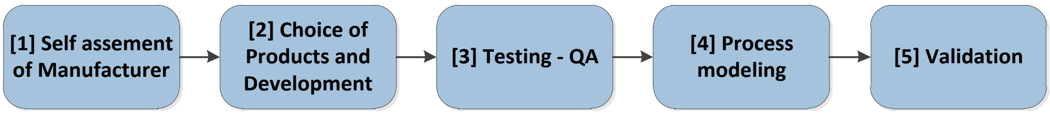

FIG. 1: Schematic representation of the development process.

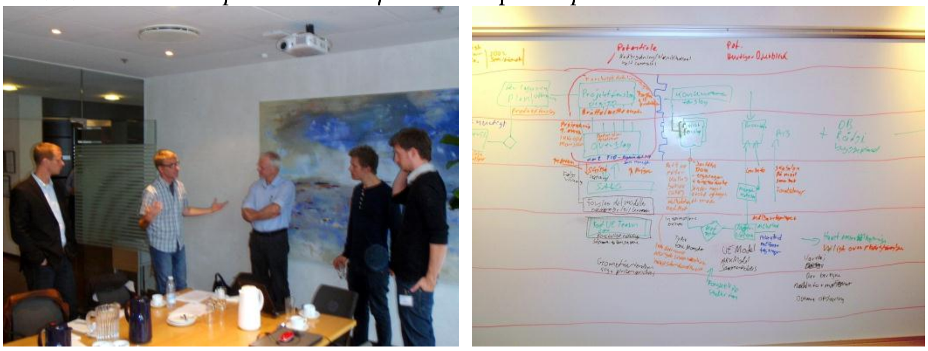

FIG 2: The expert group workshop

3.2 The Business Process

The existing process is typically sequential – starting with *design*, then *procurement*, and finally *compiling* the documents – with little opportunity for feedback between the main sequences. The *design* stage is more agile and runs in iterations that are not necessarily synchronized. Two main loops have been identified: the *program requirements* (placement of the building, aesthetic design, and performance requirements) and the *conceptual design* (the structural system, main routes for MEP, and choice of products and materials). The process is a compact version of the design and procurement of a traditional project and takes typically 4 to 6 weeks.

During design, the estimator keeps track of the costs (two or three complete estimates). Before placing the bid, the prices needed to be covered by subcontractors or manufacturers. Communication is increasingly unstructured (for example, telephone conversations, emails, and file sharing). Designers lack knowledge about cost and constructability and want feedback on multiple design alternatives. Sub-contractors and manufacturers are rarely invited into the design, but often based on personal preferences and experiences or through the sales function of the manufacturer. Engineered-to-Order companies are more likely to be part of the design process, but not necessarily at the bidding stage. When Made-to-Order companies are involved, they often have to spend time adjusting products or design with each other. Involvement of Made-to-Stock products is limited to a quantity take-off.

For *procurement*, the sub-contractors and manufacturers receive a closed design without the opportunity or incentive to change it. In this context, their main challenge is the effort spent on information management (*"Sometimes we get 80 drawings; how do we find the right one?"*) and quantity take-off (*"Mostly we cannot even get a DWG drawing, which is easier to take measures from!"*). The output is a bid, including a specification of the costs and products. The last sequence is *"the time where the project manager does not sleep"*, compiling documents, prices, and presentation into a bidding document.

The improved process (see Fig. 2), which integrates sub-contractors and manufacturers, can lead to a more cost-efficient design with fewer design errors. This has been shown in the literature and in practice, and has also been identified by participants. The improved process is built on *direct* participation, whereby knowledge is communicated by humans, and *indirect* participation, in which knowledge is communicated by computers through logic.

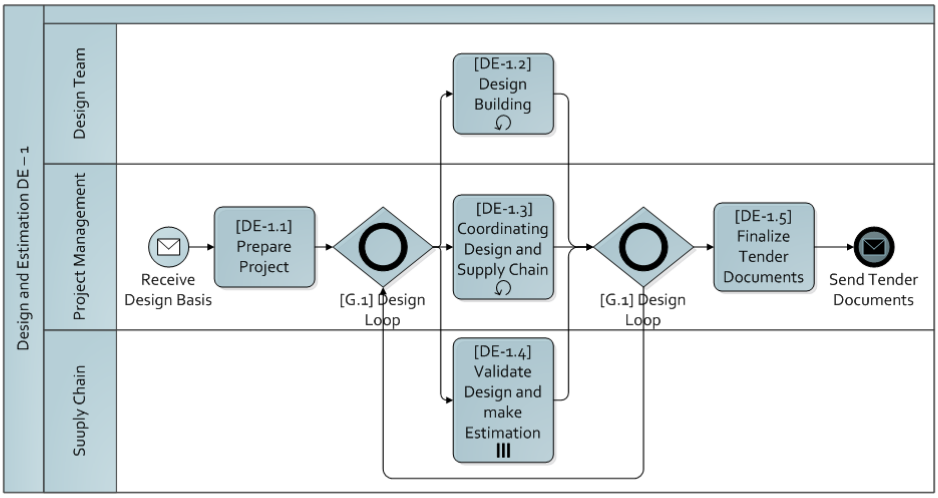

FIG. 2: Overview of IDM process

The design team makes a product model of the conceptual design using product-specific objects that have been developed and maintained by the manufacturers, instead of using generic objects. These objects are loaded to a BIM authoring tool (see Fig. 3) and equipped with simple rules (see Business Rules) to validate the design (for example, windows come in certain sizes); if the requirements are not fulfilled, the designer is notified. Information that a designer would previously have had to find by searching in a product information sheet or by contacting the manufacturer is integrated into the object. In this way, the manufacturer participates *indirectly* in the design. Afterwards, the product model is shared and can be accessed by the other designers, contractors, and manufacturers. In order to provide input that cannot be coded into the objects and for cost estimations, it is still necessary to involve the sub-contractors and manufacturers who participate *directly* in the design. Cost cannot be coded into the objects because product and labor costs depend on external factors, such as the volume of orders.

Ideally, project management can focus on coordination; forwarding the design to the sub-contractors and manufacturers and, vice versa, the design feedback and cost estimation to the design team. The product-specific objects also enable manufacturers to identify their part of the design and the IDM ensures that the necessary information is in the object (see Section 3.3). This enables the manufacturers to perform their tasks (estimation) with less effort spent on information management and quantity take-off. This frees up time that can be used to analyze design alternatives and provide valuable feedback to the design team beyond costs.

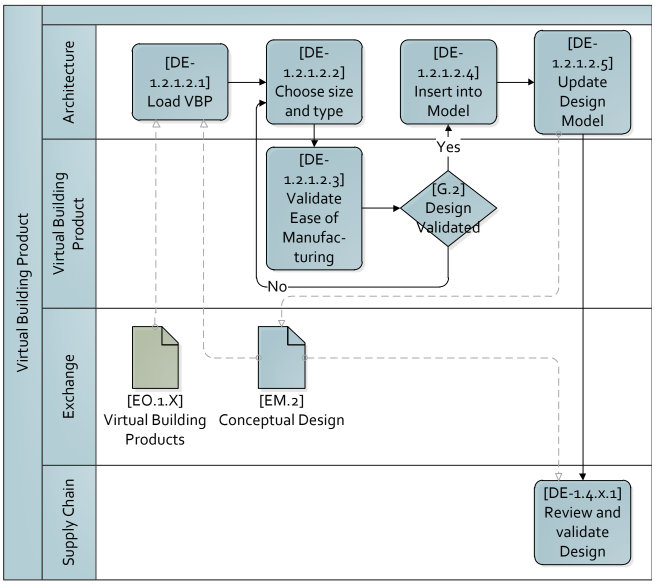

FIG. 3: Working with the Virtual Building Product

3.3 The Exchange Objects

All types of products (ETO, MTO, and MTS) have the same basic information (see Table 2). ETO products that the manufacturer designs (that is, pre-cast concrete and lightweight pre-cast concrete) require additional information from the designers, such as structural system, load, and principal details. Traditionally, some of this information has not been communicated through CAD and requires additional documents, such as the structural load analysis.

Passenger elevators (MTO) are highly standardized and do not require a lot of geometrical and other information. More important are the business rules, to ensure that the elevator fits the shaft designed. For windows, doors, and façades (MTO) the space defines the requirements for the object (e.g., solar shading, noise reduction, safety, security, and fire). Manufacturers are also interested in the energy performance analysis to optimize the product choice. MTS products (insulation, drywall, ceiling, and floor) also need attributes that are derived from space (such as fire rating, noise reduction, robustness, and applicable surface requirements).

TABLE 2: Common information in all exchange objects.

Attribute	Data Type	Actor supplying	Documentation
Object Type	String	BPM	The type of building product
Manufacturer Name	String	BPM	Name of the manufacturing company
Model Number	String	BPM	Manufacturer’s name/number of the product
Weight	Number	BPM	The lifting weight of the product (in kg)
U-Value	Number	BPM	Heat transfer coefficient of building element.
Links	hyperlink	BPM	Link to installation documentation
Material	Object	BPM	Name, quality, strength
Geometry	Numbers	BPM	Geometry that allows measures to be taken
Dimensions	Numbers	BPM	Dimensions that allows measures to be taken

3.4 The Business Rules

An important and obvious business rule is that objects can only have sizes and dimensions that are available for order. By way of example, two such business rules are explained in detail. The first issue is related to windows. According to the manufacturer and the contractor, the size of the opening (that is, a hole in a wall) must be the same size as the window including caulking. Normally a window has 12.5 mm caulking on each vertical side. However, when two windows or doors are adjacent the caulking must be 10 mm (see Fig. 4).

The second example is passenger elevators. In addition to the lifting shaft, an elevator requires an overhead on top and an elevator pit in the bottom for the lift system and other technical installation. The size of these depends on the model and make of the elevator. According to the manufacturer, a common issue is that the chosen elevator does not fit the shaft, either in depth or width, or that there is not enough room for the pit or overhead. This can be costly if it is discovered after the precast concrete elements are manufactured. Thus, one business rule for the elevator ensures that the width and height of the shaft is adjusted with the elevator design.

[BR-3] Window/Door Width

Type	Business Rule
Name	Window/Door Width
Documentation	It is mandatory that the width of an window/door is equal to the width of the opening subtracted 10 mm for each vertical side adjacent to another window/door and subtracted 12,5 mm for each vertical side not adjacent to a window/door.
Related to Concepts:	• [VBP-2.1.1] Window • [VBP-2.1.2] Glass Door

FIG. 4: Example of a Business Rule

3.5 Validation

The IDM and the BIM objects were validated in three stages: a test project, follow-up discussions with participants in the working group, and interviews with a wider group of supply chain actors. The test case was based on a minor residential project designed by an architect. The BIM objects were loaded in the model after the design was finished to simulate real life conditions; it cannot be presumed that the architect will use the product-specific objects. This led to an unanticipated proof of the value: the elevator designed by the architect was too small (see Fig. 5). The design was shared with the manufacturers in three formats: Revit, a Solibri Model Checker Information Take-Off highlighting the necessary attributes, and a DWF file for viewing purposes. The manufacturers were asked to review the design and give feedback on cost, design improvements, and specifications. Finally, the IDM was presented in an interview to a separate group of sub-contractors.

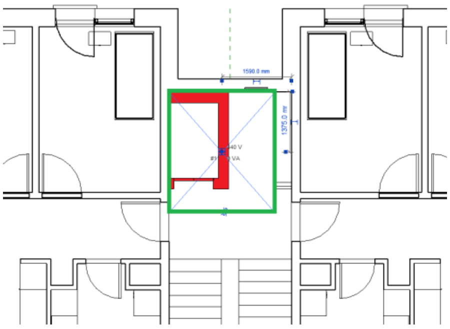

FIG. 5: The elevator as designed (red) and as ordered (green)

4. RESULTS

The IDM builds on the BPMN to model process, as an established modeling language; it is able to capture the sequence and interdependence of tasks. Furthermore, the swim lanes (that is, actors or organization) address *who does what*, meaning that, supplemented with narratives, the organization can be well described. It can become trivial to describe the organizations and actors, since many roles in a construction project are well defined. References to definitions provided by other sources (such as OmniClass) could help.

IDM distinguishes itself from other process modeling languages in the way it addresses information. The Exchange Objects enable the detailed specification of information requirements to perform a task, rather than just addressing documents, the content of which might remain a black box in other approaches. This study used the IDM to describe information requirements to a proprietary format (Revit) and to define the *set of information* that needed to be exchanged independent of the *data structure*. The set of information could be exchanged in different *structures*, such as IFC, Revit files, and even in unstructured documents. To professionals, it is more important to communicate the necessary information (for example, "*I need to know the size of the window by Monday*") than whether that piece of information comes in an IFC model, a Revit file, an e-mail, or a phone conversation (although other considerations, such as traceability, could cause one to be preferred over the other). Mapping the information set to a data structure is the responsibility of the systems developer. This is why the IDM needs to be free of IFC bindings. The information, however, should be collected as data sets representing building products, to also support the way users think about information.

The IDM's business rules are a container for design knowledge, functionality, constraints, and transformation of information. The project used narratives to communicate business rules as suggested by the IDM. Narratives are ambiguous and can take a long time to capture the essence. A precise modeling language is beneficial for the brief communication of business rules, and it also ensures that the business rules are universally understood. The Production Rule Representation (PRR) of the Object Management Group (OMG 2009) provides a standard to express rules as syntax similar to programming languages (see Fig. 6).

```
rule: Not Adjacent to Window or Door
ruleVariable:
    side : Side = window.Sides->any()
condition:
    side.IsVertical()
    and
        not side.IsAdjacentTo(typeOf(Window))
            or
        not side.IsAdjacentTo(typeOf(Wall))
action:
    window.Width -= 12.5 mm
```

FIG. 6: Example of Production Rule Representation of the window width rule

IDM enforces the analysis and description of multiple perspectives of a process, and its context, which is necessary for developing an information system. To this end, IDM is a *check list* to ensure exhaustiveness. Unfortunately, this exhaustiveness is also the greatest disadvantage, since an IDM is not concise; most IDMs cover 50, 60, or more pages. This makes the methodology more suited than the product to make requirements to building product manufacturers and their BIM objects.

Construction project processes are highly flexible and, in today's practice, it is cumbersome to model a process in great detail in order to standardize it. Not only is the order of task execution different from project to project, but the interaction between organizations can also differ within a single project. A progressive window manufacturer may want to get involved in the design, while a more conservative one wants a list of his deliveries. The real world can turn out to be very different from the model, depending on the context, and it is counterproductive to trust a detailed model that has been made for the wrong purpose. Trying to map the sequence in these processes is a huge effort and it can be very time-consuming to collect the input from multiple sources. In addition, professionals can rarely recognize and accept the same processes, because they perform them differently. The challenge is to keep the processes general enough to suit different needs and specific enough to remain relevant. The result of a generic work-flow is not necessarily applicable in specific project. This is why modeling the process by tasks sequence has a low priority and must be high order and flexible; this also reduces the chances of getting lost in modeling process and *over-modeling*.

If it is not possible to standardize processes on construction projects, since they are unique and ever-changing, information systems need to support this. IDMs could contribute as a standardized way to communicate processes on construction projects. If construction projects documented their processes and information needs in a unified way, overtime processes could be combined and reused on projects and, finally, researchers could analyze processes for effectiveness and efficiency leading to improvement. In order to become functional on a project basis, IDMs lack the ability to address points in time. While they provide the sequence, they fail to address the actual date when a task needs to be performed and information needs to be exchanged. In the context of a project, the collaborative modeling and re-engineering of a workflow could define what information is needed to perform a workflow, ideally pulling the information from the previous actor. A simplified IDM could provide the methodology and the modeling language to make this work uniform.

Business rules can capture atomic parts of the workflows, which are so small and simple that they are part of many projects and so time-consuming that automation becomes relevant. An example is the business rule that provides the window size. It is a regular problem that is simple to implement in existing BIM software and it can prevent costly erroneous orders. Information needs can be so general that they are easily implemented as attributes into BIM objects. IDMs, on a project basis, can provide a lead and help identify business rules and attributes. However, to provide requirement specifications for companies developing BIM objects, the business rules and attributes must be compiled to a much simpler format to avoid overburdening the developers.

5. CONCLUSION

The Information Delivery Manual encourages consideration of information in terms of informational elements or objects and attributes rather than informational products (that is, documents), thereby enabling actors to analyze their information needs in detail. The collaborative method helps achieve multiple inputs for modeling the workflow, although this implies a great effort. The exhaustiveness of an IDM is also its greatest disadvantage; it is time-consuming to develop and communicate on projects. Rather than being a methodology to identify informational need on an industry basis, the IDM could be applied to identify processes and information needs in projects. Over time, the collection of these processes will enable professionals to choose processes. The main focus will not be to develop an information system, but to adjust the information exchange to suit the needs of the actors. In order to be applied to projects, the IDM must be able to handle time as points in time rather than sequences. Furthermore, the IDM needs a more concise terminology, a clear selection of detail level, and a strict de-selection of trivia. The IDM cannot be applied as requirement specifications for the development of BIM objects, because of its extent, but can form the basis upon which to compile the same.

This leads to the following suggestions related to the implementation of the IDM on a project basis: (1) Task sequence should be modeled at a high order; (2) the IDM must handle points in time; (3) The narrative description must be reduced by not requiring descriptions of well established roles; (4) the IDM should be completely independent of data structures; and (5) Business rules must be communicated unambiguously; for example, by a business rule modeling language such as PRR (OMG 2009).

6. ACKNOWLEDGMENTS

The authors would like to express their gratitude to all of the people and companies involved in this study. We would especially like to thank MT Højgaard for its support and for providing access to its supply chain; the Ejnar and Meta Thorsens Foundation for funding this research; Rolf Büchmann-Slorup, Henning Roedel and Peter Bo Olsen for their valuable feedback; and the Charles M. Eastman Top PhD Paper committee at the CiB W078 2011 for giving their award to an earlier version of this paper.

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Appendix D Paper D – Builders' Perceptions of Problems with Design Information from Building Information Modeling

Builders’ Perceptions of Problems with Design Information from Building Information Modeling

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Abstract

The literature reports that the quality of design information influences the quality of construction work and the resulting building, and problems with design information can thus manifest as cost overruns, delays or defects. Building Information Modeling (BIM) is expected to improve the quality of design information. However, improved design information will only lead to better outcomes when it meets the information needs of builders in planning and executing a construction project. The aim of this study is to identify the design information problems (DIPs) that builders encounter in the planning and execution of a construction project using design information created with BIM techniques. The study applies qualitative studies to suggest nine categories of DIP and what they mean to builders.

Keywords: design information, Building Information Modeling, virtual design and construction, information quality, information management

1 Introduction

The architectural, engineering and construction (AEC) industry is driven by information. The information flows from the design team, who create the design information, to the builders, who enable the planning and execution of the construction project. This process thus makes design information a topic of great interest. AEC professionals spend a significant amount of time managing information, e.g., designers spend up to 54% of their time addressing information flows [1]. Furthermore, inadequate design information leads to unintended outcomes, as indicated by extensive research on building defects [2], schedule delays [3] and cost overruns [4].

The information flow in the AEC industry is more complicated than that described by the simple model above. However, the main information flow is in this direction, and more complexity is not necessary in this study. Design information is the medium used to communicate the form, function and behavior of a product to a user. Design information is created by the design team, in this case, architects, engineers and design consultants, but it is also generated by manufacturers and subcontractors. There are a multitude of users, but this study focuses on the subset of design information that enables builders to plan and execute construction projects. This subset currently consists of drawings (cross-sections, details, floor plans and elevations), specifications for the different disciplines, schematics and schedules. As the design evolves, changes are covered by addenda, answers to requests for information (RFI) and change orders. The traditional medium of design information is documents. Quality in its simplest definition is ‘fitness for purpose’ [5]. In this sense, the quality of design information is the degree to which it enables the builder to plan and execute the construction work successfully.

The emergence of Building Information Modeling (BIM; [6]) and Virtual Design and Construction (VDC; [7]) in the AEC industry implies the replacement of documents with digital integrated information, thereby improving the quality of design information. Research has established that BIM and VDC techniques can improve the design process [8,9], design review [10], the builder's estimation [11], planning [12] and work coordination [13] and can facilitate prefabrication [14].

Information quality issues are not unique to the AEC industry, and generic frameworks for describing information quality have been developed in the fields of computer science and information systems [15-17]. However, AEC projects involve a multitude of participating organizations with diverse backgrounds in terms of their size, education and technological maturity. Therefore, many information transactions take place through a myriad of channels, which distinguishes the AEC industry from other industries with more streamlined information flows. Thus, information problems in the AEC industry are worth studying.

The BIM and VDC techniques are expected to improve the quality of design information under the inherent assumption that better design information leads to a higher-quality outcome. This study was inspired by Wang and Strong [16], who, in their well-known study 'Beyond accuracy', argue that information quality must be understood from the user's point of view. In this case, builders are the users of design information and use it to plan and execute construction projects. Consequently, if design information quality can be improved, builders can improve their practices.

Builders do not possess the terminology to describe the quality of design information beyond accuracy. For this study, builders were asked to define the quality of design information, and their responses concluded that quality design information is obtained from drawings that accurately illustrate dimensions and contain no conflicts between building elements. The builders had a sound conceptualization of the problems they encounter with design information in their work. Consequently, design information problems (DIPs) are studied instead of design information quality because they are easier to comprehend by builders than the abstract notion of information quality.

The aim of this study is to define categories of DIP and so enhance the comprehension of the users' (i.e., builders) perception of design information. This study explores whether the DIPs noted in the literature are addressed in practice based on the use of BIM and VDC techniques. Furthermore, new kinds of DIPs that have appeared due to the presence of the BIM and VDC techniques are investigated. Innovation can address known problems, but new problems can appear simply because the awareness of problems increases when a solution exists. Qualitative methods, such as ethnographic observations and interviews with builders whose companies have at least used BIM and VDC as tactical solutions, along with interviews with experts in construction management methods were applied in this study to investigate the builders' DIPs.

This study found nine categories of DIPs identified by builders, viz., problems related to access, coordination, correctness, distribution, format, handling, precision, relevance and volume. Furthermore, the known DIPs are only partially addressed by the BIM and VDC methods and because the builders' practice for handling information has not changed sufficiently. However, this study identified a number of new DIPs due to the increased problem awareness derived from digitalization.

This paper is organized into the following five sections. First, the current section introduces the field and the research aim and our motivation for the study. In the second section, a literature review establishes the current knowledge base. The third section, Research design, establishes the methods of this study. The results and findings of this study are presented and discussed in the fourth section. Conclusions are provided in the fifth and final section.

2 Literature review

This section first reviews the literature on schedule delays and building defects. These studies typically discuss a multitude of causes for delays and defects but are not specifically designed to address questions about DIPs. The literature is reviewed to identify causes related to DIPs to establish whether delays and defects are related to DIPs and to explore how diversified DIPs are observed as the causes of unintended outcomes. Research related to DIPs within the AEC industry is then reviewed to establish what is known.

2.1 Schedule delays and building defects

The schedule delay literature is tangible because it presents long lists of causes for schedule delays. These delays are typically identified by or attributed to an actor (e.g., the contractor, designer or client). Table 1 shows the DIPs mentioned by various authors in the schedule delay literature as causes for a schedule delay, either those identified by contractors or those attributed to designers. The lists of schedule delays vary in length, which is why only the first 10 causes for delays were considered here. All the reviewed studies are based on questionnaire surveys and provide prioritized lists of delay causes but none provide data about the underlying reasons for the identified causes. The causes for delays related to DIPs are first and foremost related to delays in delivering design information by either the client or the designer and to faulty design information due to errors, missing or ambiguous information. Design errors are not inherently related to the information, which is why they are omitted here, although they are described in prior studies [18-20]. Design complexity, however, may be DIP-related because perceived complexity may be related to an inappropriate medium for communication.

DIP related to	Mentioned by
Delays in receiving information or decisions	[18], [21], 3 times by [22], [23], [24]
Delays in receiving information or decisions from the client	[3], 2 times by [23]
Errors in the design information	[22], [23], [19]
Incomplete information	[21], [25], [19]
Discrepancies in the design information	[22], [23]
Delays in receiving information or decisions from the designer	[23]
Lack of communication	[22]
Design complexity	[18]

Table 1. The top ten causes of schedule delay related to DIPs mentioned in the schedule delay literature.

The literature on defects and reworks is less tangible than the delay literature in terms of identifying causes, but evidence of DIPs can be found here also. Design errors and the quality of design documentation are negatively correlated [26] and affect the productivity and quality of the building project [4]. A lack of information accounts for 18% of design-induced errors [2]. Burati et al. [27] and Love and Li [28] classify design changes, design errors and design omissions without determining whether they were caused by improper documentation or incorrect decisions. Design omissions are inherently DIPs because the necessary components are not present in the information provided. Chong and Low [29] mention design errors without specification. Love et al. [30] identifies re-work as related to the quality of design information because some design changes are the result of error detection, waiting for shop drawings to be approved, and delays in procurement due to the poor quality of the documentation.

The literature indicates that DIPs are related to negative outcomes, such as delays and defects in construction work. Although DIPs can be identified as a cause, the concept is not thoroughly treated in the literature.

2.2 Problems in design information

Research on DIPs in the AEC industry is limited. However, a few groups have conducted similar research. The existing literature on DIPs is rooted in traditional practices based on documents and 2D drawings.

Study	List of DIPs identified
[31]	*Documents issued with conflicting information; Documents lacking clarity and forcing contractors to interpret requirements; Lack of definition clarity in scope of work; Mixing of prescriptive and performance specification clauses; Documents issued with incorrect or inaccurate information; Documents issued with insufficient details or dimensions; Issue of unamended standard specifications; Contractors have to rely on specification notes where drawings actually required; Lack of programming*

	to indicate the issue of critical design information; Use of catch all type clauses, requiring allowance for items not designed or specified; Documents calling up out of date and inappropriate standards/specifications; Simple project being unnecessarily over documented; Documents considered questionable in relation to project requirements; Critical explanatory notes hidden in general notes; Inaccurate or non-standard or poorly prepared Bills of Quantities; Late production of colors and finishes schedules; Specifications not designed to be split up into trade packages; Documents lack standard details;
[32]	*GA (General Arrangements/Assembly) drawings are not consistent with the equipment; Design is based on unfinished or incorrect supplier documentation; Errors and omissions in supplier drawings; Copy projects always lead to recurring errors that we use hours to correct from project to project; There are great shortcomings in the interface documentation on drawings, (not correct information as size, weight, tag number); Lacking interface within our organization between engineering, equipment, control systems, flow diagrams (the drawings are not congruent); Delays in distribution of drawings and documents; Equipment drawings change after engineering design is completed*
[33]	*Conflicting information; Inadequate specifications; Errors and mistakes; Missing information; Incomplete drawings; Software difficulties; Volume of information*
[34]	*Questionable Information; Incorrect information; Conflicting Information; Insufficient Information*

Table 2 summarizes the DIPs identified by previous scholars.

Study	**List of DIPs identified**
[31]	*Documents issued with conflicting information; Documents lacking clarity and forcing contractors to interpret requirements; Lack of definition clarity in scope of work; Mixing of prescriptive and performance specification clauses; Documents issued with incorrect or inaccurate information; Documents issued with insufficient details or dimensions; Issue of unamended standard specifications; Contractors have to rely on specification notes where drawings actually required; Lack of programming to indicate the issue of critical design information; Use of catch all type clauses, requiring allowance for items not designed or specified; Documents calling up out of date and inappropriate standards/specifications; Simple project being unnecessarily over documented; Documents considered questionable in relation to project requirements; Critical explanatory notes hidden in general notes; Inaccurate or non-standard or poorly prepared Bills of Quantities; Late production of colors and finishes schedules; Specifications not designed to be split up into trade packages; Documents lack standard details;*
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[34]	*Questionable Information; Incorrect information; Conflicting Information; Insufficient Information*

Table 2. DIP identified in the review of DIP literature.

The broadest study was conducted by Tilley and McFallan in the Australian AEC industry [31]. The study was later replicated by Andi and Minato in Japan [35], but because the method and conceptual framework were almost identical, only Tilley and McFallan's work is discussed. Their method was based on identifying DIPs using questionnaires based on the dimensions identified by experts. Although experts can provide insight, they also risk overlooking conditions that are obvious to builders.

Westin and Päivärinta [32] examine information quality by identifying 125 general problems within a large engineering and construction company; of the top 18 problems, they identify eight as being related to DIPs (Table 1). The study is based on qualitative methods and applies the Delphi method to a case study of a construction company. A drawback of the Delphi consensus approach is that it identifies the lowest common denominator, and a heterogeneous group often produces a higher-quality result [36].

Laryea [33] analyzes the quality of UK tender documents and concludes that the amount of information is significant and that DIPs are related to missing information, incomplete drawings, conflicting information, inadequate specifications, software difficulties, errors and mistakes. Her study is based on the ethnographic observation of two case-study companies. The study comprises a total of 552.5 hours of direct observation of the tender process and an analysis of the documents involved in the process.

In his earlier work, Tilley [34] suggests measuring the quality of design information using requests for information (RFIs). In his study, he identifies insufficient information, questionable information, conflicting information and, to a lesser extent, incorrect information as the bases for issuing RFIs. He studies two projects in detail and analyzes the documents and communications, addressing quality deficiencies.

3 Research design

3.1 Methods

The literature review only partially discusses the categories of DIPs. Thus, many of these problems remain unidentified, and an exploratory method is thus needed. Even the primarily quantitative approaches [31,35] rely on qualitative identifications of the issues to survey. Additionally, exploratory studies require a qualitative and inductive research method that allows a theory to be derived from empirical studies.

The research method (Figure 1) employed in this work is based on the grounded theory (GT; [37]), which involves the inductive derivation of a theory from empirical observations with no preconceptions. Hence, the study was conducted without a conceptualization of DIP categories from the literature. The techniques employed from GT include open coding, wherein groups are derived inductively from the data, and constant comparison, in which data are coded while it is collected, which allows for a comparison of previous findings with the sample. The grouping is performed multiple times (Figure 1) to derive categories of increasing abstraction, and a theory describing the subject of the study is developed.

The data in this research were collected by ethnographic observations in a case study [38] and additional qualitative research interviews [39] with builders and experts. Other authors have used various qualitative approaches to identify DIPs including observations [33,34], experts [31,35] and practitioners [32]. Thus, this study makes use of a triangulation between ethnographic observations on a case project, interviews with practitioners (i.e., builders) and experts in the field of construction management.

During the data collection, a myriad of problems were discussed, and the DIPs were identified among them. The unique problems that had not been mentioned before were then selected and coded. The first round of coding resulted in 17 high-level issues. Finally, these high-level issues were coded into nine categories of DIPs. Data collection was discontinued when no new high-level issues appeared.

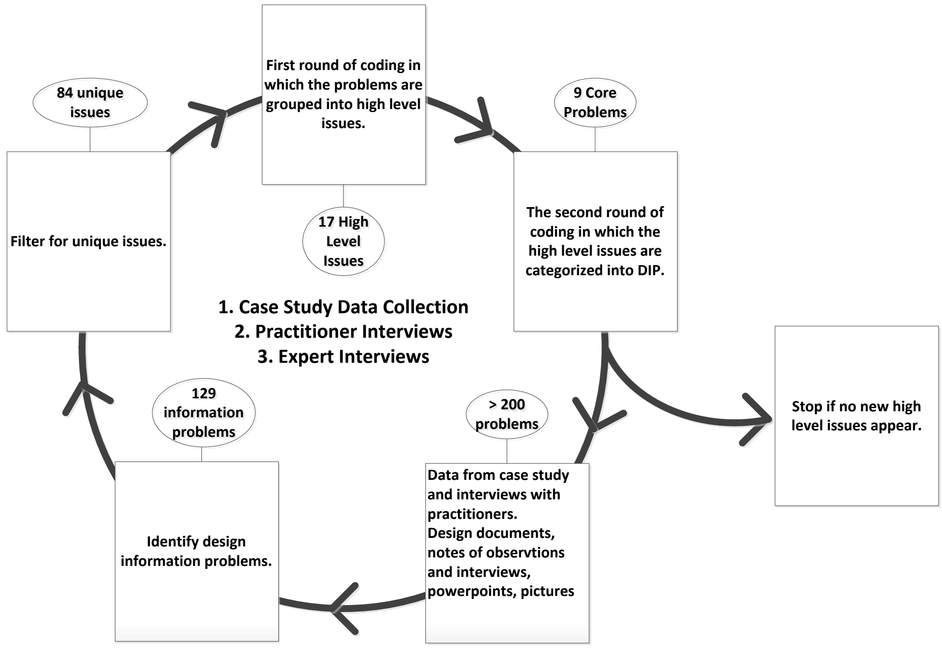

Figure 1. Research design - data collection and analysis.

The purpose of the case study was to make detailed observations of the current practices of builders when obtaining and analyzing design information. Business Process Mapping Notation (BPMN; [40]) was used to model the observed process, and the pertinent DIPs were identified using observations and interviews as well as document and communication analysis. The project studied was a commercial construction project including 35,000 m^2 of office space with a design-build contract and a project period of 3.5 years.

Builders were interviewed to substantiate the findings from the case study and to further identify DIPs. The selection for the interviews was based on the researchers' networks and knowledge of the companies' tactical use of the BIM and VDC methods. The sample was extended by recommendations from the initial sample. Up to three interviewees were present at each builder interview. A total of 16 people contributed, preferably more than one person at a time and ideally from different levels within the same organization (e.g., Directors, Senior Project Managers, Design and Project Managers, VDC Managers and Project Engineers), to provide different viewpoints on the research focus and to identify a consensus within each company. Interviews were conducted in 11 organizations (6 general contractors, 3 contract managers and 2 subcontractors). Builders often discussed their experience based on their latest project. However, in this study, the characteristics of the project are secondary. The interviews consisted of three parts: first, a semi-structured section to explore the current use of the BIM and VDC methods and current practices and problems with design information; second, a presentation of the findings from the case study to enhance the interviewees' understanding of the research and to confirm the findings; and third, a validation of the previous findings and an in-depth discussion of DIPs. The interviews were documented with notes taken during and after the interviews; these notes included narratives, observations, pictures and documents provided by the interviewees, such as drawings, slideshows and handouts, following the GT approach of "everything is data." Notes were preferred over audio recordings to encourage interviewees to provide open and honest answers.

Finally, experts were interviewed on the findings to substantiate them and to add DIPs overlooked by the builders. In total, four experts in construction management methods such as LEAN construction, BIM and VDC were interviewed in semi-structured discussions. The experts were identified by the researchers were also recommended by the builders.

4 Results and Discussion

The findings and results of this study are presented and discussed in this section. First, the identified DIPs are presented. The research method applied a two-round coding to group *unique problems* into *high-level issues* and then groups these issues into *categories of DIP*. Second, the significance of the findings is discussed. Finally, further research is suggested.

4.1 Categories of design information problems

The qualitative coding of the findings from the case-study observation and interviews with builders and experts went through two rounds of coding. First, the unique problems were coded into 17 high-level issues. Secondly, these issues were coded into nine categories of DIPs. In this section, the high-level issues identified are briefly introduced to identify whether they were known in prior literature. The DIP categories are then discussed in detail.

		Studies related to DIP					This study	
No	**High-level issues**	[31]	[32]	[33]	[34]	**Schedule delay literature**	**Case study**	**Interviews**
HL05	Ambiguous information	■	■	■	■	■	■	■
HL06	Missing information	■	■	■	■	■	■	■
HL12	Incorrect information	■	■	■	■	■		■
HL13	Distribution of information	■	■					■
HL16	Physical or digital volume of information	■		■			■	■
HL01	Timing of information	■				■	■	■
HL04	Transforming information	■					■	■
HL07	Outdated Information	■					■	■
HL08	Scattered Information	■					■	■
HL11	Lack of coordination		■				■	■
HL02	Process of finding information						■	■
HL03	Inappropriate structure						■	■
HL09	Access to information							■
HL10	Precise information							■
HL14	Interoperability between systems							■
HL15	Updating information							■
HL17	Scope of information							■

Table 3. High-level DIP issues identified in the literature through this study. Grey cells indicate that the high-level issue was identified by the study.

Table 3 presents the relationships of the high-level issues identified by the authors and previous studies in DIP, the schedule delay literature and the methods of data collection used for this study. It is important to highlight that the high-level issues were identified first by the empirical studies and were then related to the data found in the literature (see

Study	**List of DIPs identified**
[31]	*Documents issued with conflicting information; Documents lacking clarity and forcing contractors to interpret requirements; Lack of definition clarity in scope of work; Mixing of prescriptive and performance specification clauses; Documents issued with incorrect or inaccurate information;*

	Documents issued with insufficient details or dimensions; Issue of unamended standard specifications; Contractors have to rely on specification notes where drawings actually required; Lack of programming to indicate the issue of critical design information; Use of catch all type clauses, requiring allowance for items not designed or specified; Documents calling up out of date and inappropriate standards/specifications; Simple project being unnecessarily over documented; Documents considered questionable in relation to project requirements; Critical explanatory notes hidden in general notes; Inaccurate or non-standard or poorly prepared Bills of Quantities; Late production of colors and finishes schedules; Specifications not designed to be split up into trade packages; Documents lack standard details;
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[33]	*Conflicting information; Inadequate specifications; Errors and mistakes; Missing information; Incomplete drawings; Software difficulties; Volume of information*
[34]	*Questionable Information; Incorrect information; Conflicting Information; Insufficient Information*

Table 2). Thus, the high-level issues were intentionally not informed by the literature. Seven of the 17 high-level issues were not mentioned previously in the literature. The reason that all high-level issues were included in the interviews was to allow for discussion of the results of the previous observations and interviews. No new high-level issues arose in the expert discussions.

Problem type	**Related issue(s)**	**High level issues**
Access	Effort required to access design information	*HL09*
Coordination	Level of coordination among different disciplines	HL11
Correctness	Extent of missing, incorrect, or outdated design information	HL06, HL07, HL12
Distribution	Routing and distribution of the design information	HL13, *HL14*
Format	Flexibility and conciseness of the medium	*HL03*, HL08
Handling	Effort to transform or update information regarding work tasks	*HL02*, HL04, *HL15*
Precision	Representation of actual working conditions in an accurate and unambiguous fashion	HL05, *HL10*
Relevance	Timing of information delivery	HL01, *HL17*
Volume	Number of documents, files, and other media	HL16

Table 4. Types of design information problems and their related high-level issues. *Italic* font indicates high-level issues not discussed in the prior literature.

In the following section, we discuss the categories of DIPs identified in **Table 4**. Each category is introduced by listing the related unique problems and high-level issues. The category itself is then described; the causes, contexts and consequences of the problems are reviewed. This study also presents strategies and tactics for addressing DIPs perceived by the builders because the discussion of DIPs inevitably leads to methods for overcoming these problems but leaves the evaluation of the effects of these approaches for future research.

4.1.1 Access

High-level issue	**Unique problem**
HL09: Access	Traditional accessibility is less than acceptable

	Drawings in site office
	Slow access to data slows construction down

Table 5. Unique problems and high-level issues related to the DIP Category Access.

Access to the design information is problematic, regardless of whether the drawings are digital, physical or found in BIM models (Table 5). The most up-to-date set of physical drawings for a construction project is often located at the site office, which is time-consuming to access because the subcontractor must travel a physical distance. Additionally, it can be difficult to identify the current version and to retrieve the complete, updated set of drawings. A digital version of the design information is often placed on a project-specific web site, which can be accessed through mobile or stationary devices. However, this design information is not always available; furthermore, the project-specific web site is often accessible to the GC and the designers but is not always available to the subcontractors. Many problems stem from this issue, but these can be summarized by stating that the information that the builders need is unavailable. The strategies used to address this problem include granting access to the project-specific web site to everyone who needs it and placing large screens on-site and providing mobile devices.

4.1.2 Coordination

High-Level issue	Unique problem
H11: Lack of Coordination	Encourage designers to coordinate
	Uncoordinated design documents
	Collisions in building systems

Table 6. Unique problems and high-level issues related to the DIP Category Coordination.

The coordination of the geometry, also referred to as spatial coordination, building system coordination, conflict detection, or constructability review, is performed to avoid conflicts among building elements. A lack of coordination is a problem typically observed in practice based on 2D drawings. We observed that the BIM and VDC methods were primarily applied to coordinate through conflict detection and coordination meetings among the relevant designer and builders (Table 6). Thus, the extent of coordination in BIM and VDC is limited. Coordination is included as a DIP because it is the primary criterion used by builders to define information quality.

4.1.3 Correctness

High-level issue	Unique problem
HL06: Missing information	Architects model only what they have to
	Assuming what the design implies
	Uncertain that everything is in the model
	Insufficient information
	Missing information
	Missing product-specific information
	Only geometry is present in the model
	Information not in model [but in documents]
HL07: Outdated information	Copy-paste in the specifications
	Require current versions of models/documents
	Outdated information
	Outdated product information
	Outdated drawings
HL12: Incorrect information	Wrong Product
	Illegal products

Table 7. Unique problems and high-level issues related to the DIP Category Correctness.

Problems with the correctness of the design information manifest as missing, outdated or profoundly incorrect information in BIM models, documents, specifications or drawings (Table 7). Products that are not authorized according to legislation, standards or professional practice are termed incorrect products. The problem of outdated products is caused by the use of building products that change more often than designers update their catalogs. Another reason for the presence of outdated products is the so-called "copy-paste" design, in which parts of older projects are reused. A strategy to address this problem is to involve subcontractors and building product manufacturers in the design process.

4.1.4 Distribution

High-level issue	Unique problem
HL13. Distribution of information	Preparing models for further processing
	Communicating changes
	Losing design changes
	Managing information
	Forwarding RFI responses
	Routing information
	Sharing information
HL14: Interoperability	Interoperability with facilities management
	Information in native systems

Table 8. Unique problems and high-level issues related to the DIP Category Distribution.

The distribution problem is twofold (Table 8). First, the routing of drawings, RFIs, RFI answers, addenda, submittals and a myriad of emails must be screened for relevant information. AEC professionals spend a significant amount of time on this task (up to 54% for designers [1]). Second, the interoperability and easy exchange of data between software systems cannot be taken for granted. If interoperability is not available, the information must be re-entered or adjusted manually. The problem of interoperability is also related to the transference of data to facility management systems. Distribution problems are time-consuming. Project-specific web sites can address the first part of the distribution problem, but no clear strategy for interoperability is observed when the same software cannot be used by all parties involved in the project.

4.1.5 Format

High-level issue	Unique problem
HL03: Inappropriate structure	Document-based process
	Information tracking
	As-built drawings were drawn by hand
	Drawings represent the legal basis
HL08: Scattered information	Addenda
	Answers to RFIs
	Many RFIs
	No specifications in the model

Table 9. Unique problems and high-level issues related to the DIP Category Format.

The format or structure (e.g., paper documents, digital documents or databases) of the design information is inflexible, and information is distributed among multiple documents (e.g., BIM models and specifications; Table 9). Drawings have acted as the contract between the design and construction teams for centuries [41]; many tasks are based on drawings, even when BIM models exist. Information is scattered because designers work with a view of the entire building (e.g., plans and elevation models), whereas builders work with building products that will be viewed at multiple levels. Some subcontractors address issues with the structure of the drawings using *enhanced* shop drawings, which include all of the information necessary for installation in the field. This information is at least partially extracted from the models created by BIM and VDC methods. In general, linking more information to the models ameliorates this problem.

4.1.6 Handling

High-level issue	Unique problem
HL02: Process of finding information	Difficult for specific tasks
	An iterative process
HL04: Transforming information	Submissions are time-consuming
	Need for information depends on builder
HL15: Updating Information	Design changes
	Design never stops
	Freeze model on CD
	Keep information up-to-date

Table 10. Unique problems and high-level issues related to the DIP Category Handling.

Handling is closely related to format. The difference is that *format* describes problems with the information medium or product (Table 10), whereas *handling* addresses the transformation process (e.g., compiling information about a product for procurement) or changes in the product (e.g., a change in the design). The format of the information is important: a digital 3D model is easier to transform than paper, but digital models are not inherently superior in terms of ease of finding, transforming and updating information. During the interviews, design changes were frequently mentioned as a problem. Design changes are not an explicit DIP. However, the difficulty of finding, transforming and updating design information makes them inconvenient. The problem is exacerbated when changes do not include updated drawings and specifications but such updates are instead published in addenda and RFI answers. The pragmatic solution is to extract the information from addenda and RFI answers and add it to the paper drawings manually. However, this technique makes it difficult to trace changes at later stages. BIMs do not address this issue directly; thus, handling is also a collaboration-level problem. Thus, closer collaboration is expected to facilitate improved handling of information.

4.1.7 Precision

High-level issue	Unique problem
HL05: Ambiguous info.	Ambiguous specifications
	Contradictory information
	Information presented in a manner that is difficult to understand
HL10: Precise information	Receiving rapid and accountable information
	Design model not suitable for construction
	Existing conditions not reflected
	Gap between design intent and actual construction
	How the model becomes reality
	Manufacturer does not replace design
	Model only for design communication
	No trade models present
	Product not fabricated according to the model
	Lack of understanding regarding the scope of the work
	No BIM objects for production

	Tolerances cannot be absorbed

Table 11. Unique problems and high-level issues related to the DIP Category Precision.

Precision implies unambiguous information that reflects actual conditions. Even when the BIM and VDC methods are used, specifications, BIM models and drawings do not always reflect each another (Table 11). Problems arise when the design remains general rather than indicating precise and actual dimensions, specific products, and existing conditions. Laser scanning is gaining popularity for its ability to capture existing conditions. Precision is also related to the tolerances in building products specified during design; sometimes, these tolerances cannot be absorbed during construction and can exceed the overall tolerance. If a lack of precision is recognized too late, severe consequences may follow at the construction site. Laser scanners can provide precision measurements of the existing conditions and the erected construction work.

4.1.8 Relevance

High-level issue	**Unique problem**
HL01: Timing of information	Flow of information
	Information management
	Making information available to subcontractors pre-contract
	Manufacturers introduced late in the design or construction process
	Inability to obtain needed information
	Speed of estimation
	Time for modeling
	Knowing what information is needed and when
HL17: Information scope	Coordination model is different from estimation model
	Uncertain model contents
	Model for estimation
	No history of models
	Models not used by everyone
	Landscape not included in model
	Facilities Management information missing

Table 12. Unique problems and high-level issues related to the DIP Category Relevance.

The relevance of information requires a knowledge of the scope and timing of information delivery (Table 12). The scope is the subset of design information required to complete a task, whereas the timing is the sequence and time flow of information delivery required to prevent delays in completing the task. Designers are often unaware of the information needs of the builders, and the builders struggle to express their needs. When the design information requires clarification, the timing of the client's, designer's or manufacturer's answer can interfere with and delay the builder's work flow. The relevance can be improved by synchronizing the design sequence and information output with the builder's information needs through design pull scheduling sessions attended by both the designers and builders. This method is an instance of the Last Planner System for production control [42] and design management.

4.1.9 Volume

High-level issue	**Unique problem**
HL16: Volume	Specifications are comprehensive
	Traditional documentation is physically large
	Too many emails

	Too much detail
	Volume of documentation
	Volume of traditional specifications
	Volume of drawings

Table 13. Unique problems and high-level issues related to the DIP Category Volume.

Design information is spread across a variety of media such as emails, drawings, specifications, RFI answers, addenda and hand sketches (Table 13). Consequently, it is difficult to envision an overview of the product under construction simply due to the physical or digital volume of information. Volume is not an inherent problem of traditional documentation because a comprehensive view may be lost in both BIM and VDC practices. An example of a volume problem is the specifications of a studied US project consisting of more than 1,600 pages, making the specifications difficult for the construction team to handle. Consequently, builders begin memorizing the parts that are important to them, which can lead to assumptions. Additionally, the volume of information can cause gaps among the subcontractors and a lack of understanding of the scope of the work for the builder. A clear strategy that addresses this issue has not been developed yet.

4.2 Research significance

No new high-level issues were identified from the data in the prior literature. However, only ten of the 17 high-level issues found in this study had been previously identified in the literature. This finding is an indication of this project's significance and demonstrates the contributions of the different perspectives on the studied topic.

This study is novel because it considers the categories of DIPs from the builders' perspective under the BIM and VDC methods. The 17 high-level issues that led to the existing categories are used to code the data obtained in section 2 (Literature review) to discuss the significance of the identified categories of DIPs (**Table 3**). This dataset is limited and cannot validate the empirical findings; however, the emergence of new categories would indicate that the findings are not exhaustive, and the significance of the analysis will be supported if the data can be coded into the existing DIP categories.

From section 2.1 on "Schedule delays and building defects", the only emergent issues are the *timing of information and decisions* and *missing and incomplete information*. The underlying reasons for many of the other causes of delays, defects and cost overruns may also be problems with the design information, but this assertion cannot be established without a thorough insight into the data. The potential for preventing unintended outcomes by addressing a broader perspective is not fully recognized. New strategies to prevent unintended outcomes can be provided by establishing a solid link between the delays, errors and overruns and categories of DIPs, thereby elucidating the causes of these issues.

This study extends the knowledge of DIPs as presented by the authors cited in the literature review by applying a different scope, method and focus. However, it is interesting to note that seven high-level issues were not identified in the previous studies. One of these novel issues is the process of *finding information*. The time spent finding information was not considered by the other authors. The focus of the current document-based studies hinders the identification of possibilities for improvement. The ethnographic observation by the authors identified this issue. The same is true for the *structure* of information being inappropriate. *Precise information* is closely related to *incorrect information* because the authors presented abstractions that do not necessarily distinguish between them. It can be assumed that the reason why design changes are observed as problems is partially due to problems related to *updating information*, so this DIP is implicit in the literature. *Interoperability* is not identified as an issue because the exchange of data and information among different systems does not become an issue until the systems are digitalized, i.e., until BIM and VDC methods are applied. *Access to information* is primarily a problem for people working on-site (e.g., subcontractors). Although a general contractor can obtain access to the information he needs, this information may not be passed on to the subcontractor. Moreover, project managers are physically near the drawings in the office, which is not the case for the on-site personnel. The *scope of information* is closely related to obtaining information; the ease of determining the purpose of information is closely related to the level of integration of the information. The notion of using the design information for aspects other than drawings is also included [43].

4.3 Future research

The identified DIP categories represent guidelines for areas that need improvement, which may lead research in different fields in new directions. First, a thorough understanding of the causes of schedule delays, cost overruns and building defects in the context of DIP can lead to new insights on how to prevent them. Secondly, builders claim to develop methods to address DIPs, whereas researchers must determine the efficacy and efficiency of these methods. Third, further research can build on this categorization to suggest a framework for assessing and improving design information quality. This framework should utilize dimensions, metrics and a methodology for improvement. The dimensions of design information quality could be derived from the categories of DIPs and theories in other fields. Metrics built on the dimensions would ideally measure design information quality directly by assessing the available design information rather than surveying the perceived design information quality. To improve design information quality, the information must be made explicit. The ability to assess design information quality makes it possible to measure the effects of interventions.

5 Conclusions

We identified 9 categories of DIPs encountered by builders in the planning and execution of construction projects in the context of the BIM and VDC methods. Previous research did not take the potential of these new technologies into account and thus provides only a cross-section of the problems; the understanding of DIPs as the causes of schedule delays, cost overruns and building defects was limited. The categories of DIPs are universally valid and are unrelated to the way information is created (e.g., traditional or BIM and VDC methods). However, the awareness of innovations such as BIM and VDC methods draws attention to new categories of problems. Technological innovation is not specific to the BIM and VDC methods but to the digitalization of business processes in the wider AEC industry. Further research is needed to develop theories to describe design information quality, to understand the informational aspects of a design as a cause for unintended outcomes, to determine the effect of the builders' methods to address informational problems, and to study whether the DIP categories can be related to metrics that enable the direct assessment of information quality and whether this assessment then leads to improvements.

Acknowledgments

The authors would like to express their gratitude to all the people and companies involved in this study. We would especially like to thank MT Hojgaard A/S for their support, the Ejnar and Meta Thorsens Foundation for funding this research, the Center of Integrated Facilities Engineering for access to their member organizations and Peter Bo Olsen and Rolf Büchmann-Slorup for their valuable feedback.

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Appendix E Paper E – A Framework for Assessing Design Information Quality from a Builder's Perspective

A Framework for Assessing Design Information Quality from the Builder's Perspective

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Abstract

Building information modeling (BIM) is expected to improve the quality of the design information used by builders to plan and execute construction. However, the effect of BIM and other technological or organizational advances on design information quality (DIQ) must be better understood, and assessment is necessary to document improvements to the design information. This study provides a framework to assess and improve the quality of the design information. This framework consists of eight dimensions: consistency, correctness, precision, availability, distribution, flexibility and amount of information that define DIQ for builders, indicators and scores within each dimension for quality assessment, and a collaborative method for identifying and documenting the information requirements. The presented framework is applied to a case project.

Keywords: Information Delivery Manuals, Building Information Modeling, Design Information Quality, Information Management, Design management

Abbreviations

AEC: architectural, engineering and construction
BIM: Building Information Modeling
DIQ: Design Information Quality
IDM: Information Delivery Manual
ISO: International Standards Organization

1 Introduction

In many industries, low information quality is commonly accepted; as long as the information quality remains stable within an industry, no competitive focus exists (English 1999). In the architectural, engineering and construction (AEC) industry, 2D drawings have been the preferred form of communication between the designer and builder for more than 600 years (Toker 1985), and retrieving information is costly for AEC practitioners because of information overload and the lack of high-value information (Tang et al. 2008).

Building information modeling (BIM; (Eastman and Siabiris 1995)) is currently replacing the traditional medium of design information in the AEC industry (i.e., documents) with integrated digital information (i.e., BIM models) (Eastman 1981). Geometric, information-bearing 3D models of buildings (Eastman and Siabiris 1995) are also being used to analyze the performance criteria for design, construction and operation (Fischer 2006). BIM is becoming increasingly popular in the AEC industry, and one of the perceived benefits for AEC practitioners is the graphical organization of the information (McGraw-Hill 2009).

Design information is used by builders in the planning and execution of construction work. Banker et al. (Banker et al. 2006) provided empirical evidence from industry that information systems improve plant productivity. Thus, improving design information can potentially improve productivity and product quality (i.e., building quality) in the AEC industry. BIM has the inherent promise of improving design information. Previous research indicates that even when design information is created with BIM, builders encounter design information problems when planning and executing construction work (Berard and Fischer 2012). To improve design information quality (DIQ), it is necessary to thoroughly understand what DIQ means to builders and how it is measured. Therefore, DIQ must be better understood, and methods for DIQ assessment should be identified.

Traditionally, the design team consists of architects and engineers, but manufacturers and subcontractors also supply design information. Design information is a product or service used to communicate the form, function and behavior of a design (Clayton et al. 1999) to a receiver (i.e., a customer). Builders are important receivers for design information because they use this information to plan and execute construction projects. Hence, builders and designers engage in a customer-supplier relationship with respect to a product, namely, design information.

To successfully measure DIQ from the builder's perspective, two prerequisites should be fulfilled. First, the information must be considered in the context of the task (Wang and Strong 1996, Eastman et al. 2010, Boddy et al. 2007). Furthermore, the information exchange on AEC projects cannot be predefined from the beginning to the end of the project because the processes involved in executing tasks and the required information needs vary depending on the project, the participants involved and the events that occur during the completion of the project (Hartmann et al. 2009). Second, quality is achieved through the specification of requirements for a product by the customer. A common definition of quality is *fitness for purpose* (Juran and De Feo 2010). *Conformance to specifications* and *meeting or exceeding customers' expectations* are also generally accepted definitions of quality in the literature (Reeves and Bednar 1994). All three definitions imply the existence of a supplier, a product and a customer. *Conformance to specifications*, however, explicitly states that the customer has requirements for the product, which is the definition this study uses. Consequently, DIQ is defined in this study as the conformance of the information supplied by the design team to a builder's specifications for the planning and execution of a construction project. The two prerequisites emphasize the need to enable the builder to specify the requirements for the design information delivered by the design team.

Defining information quality has been a topic of continuous research with the goal of developing a generic framework (Naumann and Rolker 2000)(Naumann and Rolker 2000)(Wang and Strong 1996, Naumann and Rolker 2000, Lee et al. 2002) and applying it to specific areas such as healthcare (Pipino and Lee 2011), national security (English 2005) and manufacturing (Gustavsson and Wänström 2009). However, there has been little research performed on information quality in the AEC field; several studies state that information quality is a problem (Westin and Päivärinta 2011), whereas others attempt to measure information quality via questionnaires (Tilley et al. 1997, Tilley and McFallan 2000, Andi and Minato 2003). In the information systems literature, Bounhas et al. (Bounhas et al. 2010) identify a method for creating a domain-specific information quality framework, which includes four steps: the identification of information quality dimensions that are suitable for the domain and application in the existing literature, the identification of the assessment methods used for each dimension, the definition of scores and metrics for each dimension, and the determination of methods and/or formulas for aggregating the information quality measurements into a single information quality value or into multiple indices for each information quality dimension specified in the model.

The aim of this study is to provide the means to address the topic of DIQ from the builder's perspective by applying BIM. For this purpose, we propose a framework for assessing DIQ. The framework consists of three components corresponding to the first three steps of Bounhas et al. (Bounhas et al. 2010). The first component is an eight-dimensional DIQ model, which focuses on understanding DIQ from the perspective of the design information customers (i.e., builders). The second component is a set of indicators, one for each dimension. These indicators are observable events and entities related to the dimensions that can be used for assessment, e.g., by questionnaires or by observation. The third component is a scoring system for each indicator that uses a five-point scale based on the current stage of development in practice, ranging from traditional to innovative. To address the fourth step, radar charts are used to visualize the results of the case study. The ability to communicate information requirements is a prerequisite for the assessment and improvement of DIQ. Hence, this study also proposes a collaborative method for identifying and documenting information requirements based on research in design process planning (Ballard 1999) and Information Delivery Manuals (IDM; SO 29481-1; (ISO 2010)). Finally, the results are applied to a construction project by assessing DIQ through a questionnaire to demonstrate the applicability of the framework.

2 Background

This section establishes what is known about information quality from the literature and identifies the dimensions of DIQ from a builder's perspective. This identification is performed by relating the design information problems encountered by builders to the literature on information quality. Subsequently, the literature describing design process planning as a method for identifying information requirements is reviewed; finally, a system of notation for modeling the flow of information is described because both are prerequisites for DIQ assessment.

2.1 Information Quality

In the data and information quality literature, the terms 'data quality' and 'information quality' are used almost interchangeably, although there is a profound difference between data and information. In this study, the term 'information quality' is preferred. The literature also evidences a lack of agreement on the dimensions of information quality. However, two well-cited studies emerge from the larger body of information quality research. The first is from 1985, by Ballou and Pazer (Ballou and Pazer 1985), who proposed a general model for assessing data and its general quality by identifying four dimensions: accuracy, timeliness, completeness and consistency. The second study is from 1996, by Wang and Strong (Wang and Strong 1996), who argued that the notion of information quality requires a deeper understanding from the information user's perspective. Wang and Strong identified 15 dimensions: access security, accessibility, accuracy, the appropriate amount of data, believability, completeness, concise representation, ease of understanding, interpretability, objectivity, relevancy, representational consistency, reputation, timeliness and added value. Many of the frameworks proposed in the literature adapt the dimensions proposed by either Ballou and Pazer (Chengalur-Smith et al. 1999, Ballou et al. 2006, Khatri and Brown 2010) or Wang and Strong (Lee et al. 2002, Kahn et al. 2002, Pipino et al. 2002) to their work. Noting that the dimensions of Ballou and Pazer are contained in the work of Wang and Strong, we employ the latter in this study (see Table 1).

Although the literature about frameworks for information quality in other fields is comprehensive, only three studies that are specific to the AEC industry have been identified (Tilley et al. 1997, Tilley and McFallan 2000, Andi and Minato 2003). Tilley (Tilley et al. 1997) defined quality information as 'the ability to provide the contractor with all the information needed to enable construction to be completed as required, efficiently and without hindrance.' Tilley and McFallan (Tilley and McFallan 2000) employed a survey about information quality among designers and builders in the Australian AEC industry. For this purpose, they identified accuracy, certainty, clarity, completeness, conformity, coordination, final checking, relevance, standardization and timeliness. Andi and Minato (Andi and Minato 2003) applied the method and framework of the Australian AEC (Tilley and McFallan 2000) industry to the Japanese AEC industry. Hence, only Tilley and McFallan's work is considered in this study (see Table 1).

Wang and Strong (Wang and Strong 1996) recommended understanding information quality from the perspective of the information user. Considering the user's perspective is also implicit in 'conformance to specifications.' Information quality can be an abstract notion that is not easily comprehended (Gustavsson and Wänström 2009). Hence, the literature concerning design information problems is reviewed. Berard and Fischer (Berard and Fischer 2012) studied the practices of builders and identified nine categories of design information problems that builders encountered during the planning and execution of construction work: access, coordination, correctness, distribution (Browning 2001), format, handling, precision, relevance and volume (see Table 1). Other authors (Westin and Päivärinta 2011, Tilley et al. 1997, Tilley and McFallan 2000, Andi and Minato 2003, Laryea 2011) have conducted similar research that is included in the work of Berard and Fischer.

DIQ	**Design Information Problems** (Berard and Fischer 2012)	**AEC Information Quality** (Tilley and McFallan 2000)	**Information Quality** (Wang and Strong 1996)
Relevance	Relevance	Relevance, Timeliness, Clarity	Relevancy, Concise representation, Timeliness, Ease of understanding, Access security, Interpretability, Objectivity, Believability, Reputation
Consistency	Coordination	Coordination, Conformity, Standardization	Representational consistency
Correctness	Correctness	Completeness	Completeness
Precision	Precision	Accuracy Certainty	Accuracy
Availability	Access		Accessibility
Distribution	Distribution, Format		Accessibility
Flexibility	Handling, Format		Appropriate amount of data
Amount of Information	Volume, Format		Appropriate amount of data

Table 1. DIQ dimensions related to the work of relevant authors.

Table 1 presents an overview of the DIQ dimensions used in this work, which were derived by relating the design information problems encountered by builders to information quality dimensions. Please note that the dimension *value added* (from Wang and Strong) was omitted from the DIQ dimensions here. The definition of *value added* is 'data that provides a competitive edge; data that adds value to your operations' (Wang and Strong 1996); information can provide a competitive advantage when the quality is high, implying that multiple dimensions are fulfilled. Additionally, *final checking* (from Tilley and McFallan) was omitted because this term falls into the category of quality assurance according to the other dimensions and standardizations.

2.2 Design Process Planning

One prerequisite for the framework is that the receiver of the design information (i.e., the builder) can explicitly define and require which parts of the design information are required for his tasks. Only by specifying the informational requirements can the sender (i.e., the designer) of the design information deliver high DIQ. Hereby, builders and designers engage in a customer-supplier relationship. This is a pull system in that the builder pulls information from the designer. Pull systems are known from the theory of Lean (Womack et al. 2007), e.g., Kanban (Sugimori et al. 1977). A prerequisite provided by Kanban is that more parts are soon required. Batch sizes in the AEC industry are small; hence, this constant supply is not a given. Pull systems in the AEC industry are founded on the knowledge that the time period in which there is a high certainty that the planned activities will be completed (the window of reliability) is longer than the supplier's lead time for delivering the product or service (Ballard 1999). Windows of reliability are typically short in AEC; hence, pull planning is conducted every two to five weeks. Pull systems are typically applied in the AEC for construction planning, e.g., a method called 'look-ahead' in the Last Planner system (Ballard 2000).

In current practice, the planning of design activities in the AEC industry is not thorough but is based on the due dates of drawings ((Koskela et al. 1997), presented in (Ballard 2000)). Design packages are pushed at design reviews (e.g., at phase transitions), whereas subsequent information is pulled (Matti et al. 2005). Designers create task-specific views of the information (i.e., drawings) as they undertake the design (Haymaker et al. 2004); these drawings eventually become a part of the design information if a view of the design is required to elaborate on it. As a consequence, the focus of design information is not construction. The current practice of pushing information and publishing engineering views prevents builders from specifying the design information. As a consequence, improving DIQ becomes impossible (cf., the definition of DIQ).

Ballard (Ballard 1999) presented a variation of the Last Planner system's look-ahead method (Ballard 2000) for use in design process planning, the Activity Definition Model, which assumes that a decomposed task is more easily defined than a higher-level task; this decomposition of tasks is also referred to as a 'work breakdown' structure by Ballard. Here, the users of the design output pull it into their processes. Ballard (Ballard 1999) concludes that the 'joint assignment of design tasks to both provider and puller both promotes common understanding of the criteria and also ensures that resources are used first to do work that is needed now by someone else'*.* This design process planning model was applied in a case study (Ballard 2002) that concluded that the transition was not completely fulfilled, and unsound tasks were allowed into the look-ahead window.

Designers and builders could be encouraged to jointly plan the design process in regular pull planning meetings. This collaborative planning should encourage the common understanding of each other's information needs and provide a more meaningful design schedule. More importantly for this work, the output provides the information requirements from builders for DIQ assessment and improvement.

The output of design process planning can serve as an input for the design structure matrix, which was first described by Steward (1981) and has since been applied in many industries in the design and engineering to model the design of complex systems to understand the relationships and interactions among the components (Browning 2001). The real power of the design structure matrix method is that it identifies an optimal sequence of interrelated tasks. In the AEC industry, the design structure matrix has been applied in numerous studies (Koskela et al. 1997, Choo et al. 2004, Austin et al. 1996, Lahdenperä and Tanhuanpää 2000). The design matrix is usually applied to help understand the interconnection of tasks but can also be used to model the relationships between the components and even parameters (Pektaş and Pultar 2006). The design structure matrix has consequently become a useful tool for describing information requirements.

2.3 Modeling an Information Flow

Design process planning provides a means to identify the design information requirements. Documentation is only partially addressed by the design structure matrix but is, however, desirable for several reasons. Most importantly for this study, this documentation serves as an agreement between the involved parties through which DIQ can be assessed.

Notation for business process modeling provides a means to model information flow. Four perspectives describe the business processes for information systems according to Curtis et al. (Curtis et al. 1992): functional (i.e., business rules), behavioral (i.e., sequencing), organizational (i.e., participants) and informational (i.e., information elements) perspectives. A review of seven business process modeling languages (e.g., UML 2.0, IDEF3 and BPMN) by List and Korherr (List and Korherr 2006) concluded that all languages have shortcomings regarding their handling of organizational and informational perspectives, whereas functional and behavioral perspectives are generally well implemented.

The Information Delivery Manual (IDM; SO 29481-1; (ISO 2010)), a business process modeling standard for the AEC industry, was created to address these described shortcomings. The IDM has been applied to various tasks in industry (DiKon 2012) and research (Eastman et al. 2010, Aram et al. 2010). With suitable adjustment, the IDM captures the information requirements of builders (Berard and Karlshøj 2011). The major issues with the IDM are that it does not include time and that its standard is unnecessarily comprehensive. Its major advantage, however, is that the IDM is native to BIM. Another standard for this purpose is the American Institute of Architects' Model Progression Specification (MPS; (AIA 2008)). The MPS is a document that codifies BIM exchange according to level of detail, actor and phase. One BIM software company uses the MPS (Vico 2012), but this document has not been applied in research. The MPS does not cover functional aspects and only partially addresses behavioral aspects in that it discusses phase rather than sequence. The organizational and especially the informational aspects are specifically described in detail. The major drawback of the MPS is its phase-based approach, which discusses the information requirements of phase transitions. The MPS is also native to BIM.

The MPS assumes information exchange in phases, whereas the IDM provides the means for continuous flow. Continuous flow is congruent with design process planning; hence, this framework suggests using the IDM to document the outcomes of design process planning. The design structure matrix can provide the sequence, and the output can be captured both in an IDM to model the information flow (i.e., sequence, information requirements and roles) and a schedule (e.g., a Gantt diagram) to coordinate delivery dates.

3 Methods

The dimensions of DIQ have been identified by relating research about design information problems encountered by builders to research about information quality. In the following, a method for deriving the indicators and scores is presented, followed by an introduction to the construction project that was used as a test case for the application of this framework.

3.1 Indicators, Metrics and Scores

The literature differs with respect to how information quality assessment indicators are derived; Lee et al. (Lee et al. 2002) build on a quantitative method, but Gustavsson and Warnström (Gustavsson and Wänström 2009) prefer a qualitative method. The former approach is more rigorous; however, Gustavsson and Warnström chose a qualitative method because the nomenclature and conceptualization of information quality was unclear for the sample, and a qualitative method provided more specific insights. Hence, this study applies a qualitative approach.

First, industry-specific literature regarding BIM, including execution plans, guides and standards[1] was studied. From this literature, indicators and possible scores were identified. This information was compiled into a first proposal for indicators and scores. The proposal served as the input to the first focus group discussions. To reach agreement on the indicators and scores, the findings from the previous focus group were presented at each meeting (see Figure 1). These focus groups consisted of three separate groups; BIM experts (i.e., the BIM department of a construction contractor), BIM users (i.e., a construction contractor's development group for BIM-based estimation) and BIM academics (i.e., a BIM research group at a university). Rather than collecting quantitative data, focus groups were used for validation because awareness of the technology's potential is crucial in identifying indicators and scores.

[1] The following documents were consulted:
Common Design Workflow Checklist, 2008, FIATECH, Austin, TX, USA
AutoCodes Project: Phase 1, Proof-of-Concept Final Report, 2012, FIATECH, Austin, TX, USA
BIM Guide Series, 2007-2010, GSA, Washington, DC, USA
BIM Project Execution Planning Guide, 2010, The Pennsylvania State University, University Park, PA, USA
National Building Information Modeling Standard, 2007, National Institute of Building Sciences, Washington, DC, USA
BIM Management Plan Template, 2012, NATSPEC, Sydney, NSW, Australia
Model Progression Specification, 2012, Vico Software, Inc., Boulder, CO, USA
National Guidelines for Digital Modelling, 2009, Cooperative Research Centre for Construction Innovation, Brisbane, QLD, Australia
Integrated Project Delivery: A Guide, 2007, The American Institute of Architects California Council, Sacramento, CA, USA
AIA Document E202 - BIM Protocol Exhibit, 2008, The American Institute of Architects, Washington, DC, USA
The Business Value of BIM, 2009, McGraw-Hill Construction, New York, NY, USA
BIM Execution Plan, 2012, Indiana University, Bloomington, IN, USA

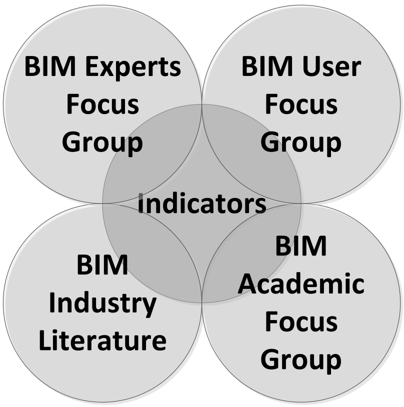

Figure 1. Model of the empirical research method.

3.2 The Case Study

The results of this research were validated in a case study. The project was the construction of a 10,000 m^2 shop and maintenance building for a regional train system, with a design-build contract of approximately € 36 million. The design phase was 8 months, and the total design-build period was expected to be 2.5 years. The design and planning were parallel activities; procurement and scheduling of the execution were concurrent with design. Consequently, the design team and the project management were both located at the construction site. All of the design disciplines prepared geometric 3D models of their design using BIM authoring tools, and the files were shared through a project web site.

The framework was applied in a questionnaire based on the indicators, metrics and scores developed in this study. In total, 11 people, including 4 designers, 4 project managers and 3 subcontractors, were interviewed and their responses scored. The questionnaire was conducted during an interview with a research assistant. The results were visualized in radar charts.

4 Results and Discussion

First, the framework and its indicators and scores for measuring the dimensions of DIQ are presented. Second, the results from applying the framework to the case study are reported. Third, the validity and contribution of the results is discussed. Finally, additional research is suggested.

4.1 The Framework

In this section, the dimensions of DIQ (cf. Section 2.1), their indicators and scores are discussed. The framework is based on the concept that dimensions and indicators should not change when new technology is developed; the scores, however, reflect the current state of technology. The scores presented in Table 2 reflect a range comprising traditional practice (score = 1), typical practice (score = 2), advanced practice (score = 3), best practice (score = 4) and most innovative practice (score = 5). This range is similar to the Stanford University CIFE VDC Scorecard (Kam 2012). Each dimension, indicator and score is discussed in detail in the following section. The scores have two purposes: they allow for the comparison of DIQ in multiple projects or the same project over time and the scores constitute a benchmark that suggests methods for improvement. The data that require scoring can be collected in multiple ways, such as through questionnaires, observations, expert scoring and automatic measurements.

Dimension/ Indicator	**1**	**2**	**3**	**4**	**5**
Relevance/ Information flow	Builder’s information needs are not identified; design information is	Builder’s information needs are not identified; design information is	Builder’s information needs are identified; design information is	Builder’s information needs are identified; design information is	Builder’s information needs are identified; design information is

	sent at the end of each phase; sender is not able to fulfill specific information needs.	sent continuously; sender is not able to fulfill specific information needs.	sent at the end of each phase; sender is able to fulfill specific information needs.	sent continuously; sender is not able to fulfill specific information needs.	sent continuously; sender is able to fulfill specific information needs.
Consistency/ Review and coordination process	Only coordinates, grids and naming conventions are shared.	Requirements are coordinated in a collaborative process.	Geometry is coordinated using software.	Building code requirements are coordinated using software.	All functional and behavioral requirements are coordinated using software.
Correctness/ Information correction process	Design team is not available to provide correct information. (>4 weeks)	Request for information process has to be followed (1-4 weeks)	Correct information is achieved by an informal process. (5-7 days)	Correct information is achieved by a fast-track process. (3-4 days)	Design team is able to provide correct information quickly. (1-2 days)
Precision/ Level of detail	Specifications are unambiguous.	Dimensions are sufficient for scope.	Level of detail is sufficient for scope.	BIM objects reflect production parts.	BIM objects reflect actual products.
Availability/ Digital distance	Paper documents at the office.	Digital documents at the office.	Digital documents in a notebook.	Digital documents at the place of production.	Digital documents on a mobile device.
Distribution/ Information distribution	Broadcast (information push).	Receiver chosen manually (information push).	Receiver chosen by role (information push).	Receiver subscription (information pull).	As specified by information requirements (information pull).
Flexibility/ Design information medium	Documents.	Editable documents.	Geometric 3D models.	Building information models.	BIM according to information requirements.
Amount of information media/ Medium of design information	Documents.	Digital documents (not versioned).	Digital documents (versioned).	Multiple 3D models and specifications.	Integrated 3D models and specifications.

Table 2. The 5-point scales to score the dimensions (1 = undesirable; 5 = desirable) of each indicator.

4.1.1 Relevance

Relevant information involves receiving the required information for the identified scope in the correct sequence at the time it is needed. Whether the required design information has been delivered indicates the relevance. With a BIM model and a sufficiently detailed information delivery schedule, automatic assessment is possible. Consequently, aspects such as the percentages of the planned completed and delivery delays can be measured.

The method chosen to establish the flow of information during the project is another potential indicator. This indicator can be assessed with three parameters: whether the receiver is able to identify and specify his information requirements to enable him to conduct his tasks, whether a continuous information flow can be established (rather than delivering information at the end of each phase) and whether the sender is able to understand the receiver's information requirements and act accordingly.

Relevance is closely related to the overall DIQ because the majority of the other dimensions cannot be assessed when an information flow between the receiver and sender cannot be established. Identifying, specifying and organizing data into a sequence and providing a time schedule according to one's confidence in the sender is crucial to evaluate the DIQ. Consequently, a collaborative technique for identifying the scope, requirements and sequence of information is provided later in this section.

In common practice, information exchange often happens at the end of each phase (e.g., as detailed designs or construction drawings), and the scope of the delivery of design information is based on the practices, habits and assumptions of the design team, rather than specification of the builders, who are often unable to detail their needs. The most innovative practice results in the required information being delivered according to an agreed-upon schedule.

4.1.2 Consistency

Consistent design information involves coordinating geometries (e.g., solving clashes between building systems) and compliance with all of the requirements for the construction work (e.g., client requirements, legislative and regulatory requirements). This coordination should be performed within the design information that is delivered by the design disciplines and the construction trades. Furthermore, the functional and behavioral requirements or the building and compliance with standards and regulations must be ensured.

An indicator for consistency is identified as the review and coordination process that is performed during and after design. The focus group interviews identified the lack of a shared frame of reference for coordinating design information (i.e., coordinate systems, module grids and naming conventions) as a major issue for multidisciplinary coordination, and industry literature supports this finding. Collaborative coordination processes and the use of software to coordinate building systems are applied in current practice (Staub-French and Khanzode 2007). In best practice, software is also applied to check legislative and regulatory building code, according to both academic research (Eastman et al. 2009) and AEC industry literature. Innovative practice entails software-assisted verification of all functional and behavioral requirements.

4.1.3 Correctness

Missing, incorrect or outdated information contravenes correctness. The proactive treatment of missing information requires that the required information and the time when it is needed are identified in advance, e.g., in an information delivery schedule. Only when this schedule is defined is the designer able to include it in the design information. Incorrect design information includes products that are not allowed by legislation, standards or professional practice. Outdated information refers either to obsolete design versions or to the choice of a discontinued product.

The design informational content can indicate the degree of correctness. Missing objects, geometries and properties are easily recognized when the scope, requirements and timing are in place. However, incorrect and outdated data are more difficult to identify. Furthermore, ranking the degree or severity of correctness is difficult because incorrect design information is rarely acceptable.

Often, the treatment of incorrect information is reactive because the design information requirements have not been identified in advance. Consequently, instead of measuring the amount of correct or incorrect information, the established process for correcting incorrect design information can be assessed. The assessment is grounded in the focus group discussion and is based on the three states of correctness that a piece of design information can have: confirmed incorrect, unconfirmed incorrect and confirmed correct. A piece of information is unconfirmed correct by default; if missing, incorrect or outdated information is identified, then the state becomes confirmed incorrect until it is addressed, at which point the state becomes confirmed correct. Thus, in terms of time and effort, an indicator of correctness is the process of moving a piece of design information from confirmed incorrect to confirmed correct.

4.1.4 Precision

Precision is defined as accurate geometry and unambiguous product specifications according to the level of detail that is appropriate for the scope of work by the builders. Geometric accuracy involves accounting for production parts and actual building products rather than generic designed objects. An example for production parts is the design information for a drywall section, which is detailed as studs, drywall sheets and insulation, instead of as a complete drywall object. Even more advanced practice includes the geometry and properties of the actual products in the design. Furthermore, geometric accuracy accounts for the actual dimensions, absorbing production tolerances and site conditions. Unambiguous requirement specifications have explicit requirements and distinguish the actual design requirements from the inherent properties of the suggested products.

Precision can be assessed by the level of detail in the design information. This assessment is performed by opposing the available level of detail to that specified in the design information delivery schedule. The scale identified by the focus groups and industry literature is pragmatic and absolute. Consequently, design information of a certain scope will receive a certain score, which is not necessarily the highest when a higher precision is not desirable in the scope of the work.

4.1.5 Availability

Availability is the effort involved in accessing or gaining access to the current design information in a working situation. Because of the cost involved, the DIQ is negatively affected by increasing the distance between the receiver and the information. Availability is closely related to the amount of information, the medium and its distribution.

An indicator of availability is the 'digital distance' to the design information. Digital distance combines the physical distance and the device used to access it. A paper-based drawing archive at the construction site office is inferior to information that is available digitally at the work site or contained on a mobile device. Paper drawings are available in production; however, the use of paper drawings does not ensure that the most current design information is the basis of production.

4.1.6 Distribution

Distribution involves sharing the design information with the builders on a construction project and routing subsets of the design information to the appropriate builders. This sharing process implies not only new design information but also notifications about changes in subsets of design information. There are two basic approaches to the distribution of design information: pushing design information (i.e., the sender decides what is relevant to the receiver) and pulling design information (i.e., the receiver decides what is relevant to him).

Push-based approaches range from broadcasting all design information to everyone to role-based information distribution. Design information updates become more frequent in the integrated collaboration of BIM, making the push-based approach less viable because of an overload of notifications. Pull-based approaches can be based on the scope and timing of design information and ideally highlight information that is not ready. The information distribution approach is the indicator of the distribution dimension.

4.1.7 Flexibility

Flexibility describes an effort to change and update design information, such as when the design is changed and the design information is transformed and extracted (e.g., a quantity take off for estimation). The design information media (e.g., paper documents, digital documents or BIM models) are indicators of the flexibility. Paper documents are the least flexible because they are difficult to update; when a digital source document is not available, the paper documents must be reprinted. Furthermore, the extraction of task-specific information from a multitude of paper documents is a time-consuming task. BIM models that integrate design information previously stored in different media allow for the easiest updates and transformation of design information. Consequently, the scale of flexibility ranges from documents to integrated BIM models.

4.1.8 Amount of information media

The number and extent of documents, files, BIM models and other media must be appropriate for the project scope. A system with paper documents can absorb less information before it becomes unmanageable than can integrated 3D models. Hence, a paper system does not provide the same level of comprehension, which enables decision making based on the design information. A large amount of information is not inherently a problem; however, losing track of the design information is a problem. This phenomenon is commonly referred to as 'information overload'. Consequently, the amount of information is an indicator of the negative effect of unmanageability on the quality of the design information. The scale ranges from documents to integrated BIM models, the last not necessarily involving only one model but rather involving the establishment of links between the model and other sources of data.

4.2 The Application of the Framework

The present framework was applied to a case study project. In the following sections, the main results of two design process planning sessions and the questionnaire are presented.

4.2.1 Design process planning

We decided to implement design process planning together with design management to address reactive information requests from both subcontractors and design disciplines in each group and to provide a prioritized design schedule that supports the informational requirements. Two workshops were held, one with the design team and the relevant subcontractors and one for the design team only.

The key artifact of the workshops is a Post-It® note created by each workshop participant, describing the information that is typically delivered by her to a project and more importantly, what she needs from others to enable the delivery of information. The decomposition of the BIM model into objects resulted from the breakdown structure, rather than by reference to drawings. After filling in the notes, the participants were asked to pull the information. Starting from the desired end result, in this case drawings for approval by the municipality, each participant called up his information requirements; in this way, the design information and the design sequence were pulled.

After both workshops, there was strong anecdotal evidence that the participants were satisfied with the process and the outcome. The participants expressed that they both had the opportunity to express their information needs and had a better understanding of the other's information needs. The output from both meetings led to an update of the design schedule, which became more detailed by referring to the design of subsystems. Unfortunately, the design process planning was never taken over by the design management, and the detailed sequence identified in the workshops was never reflected in the design schedule.

4.2.2 DIQ assessment

The assessment of the DIQ by the individual respondents is illustrated in

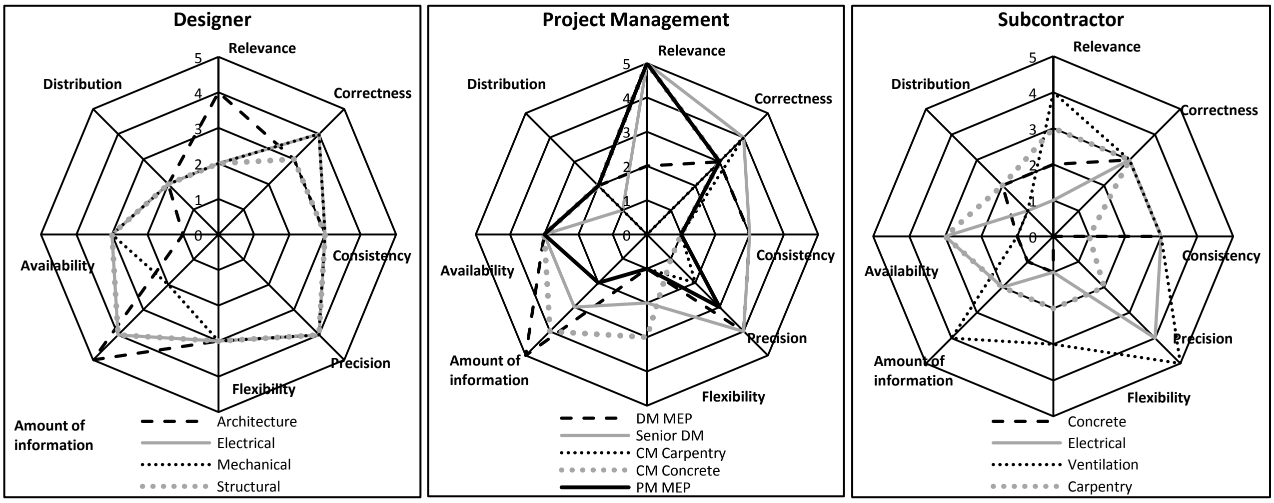

Figure 2.

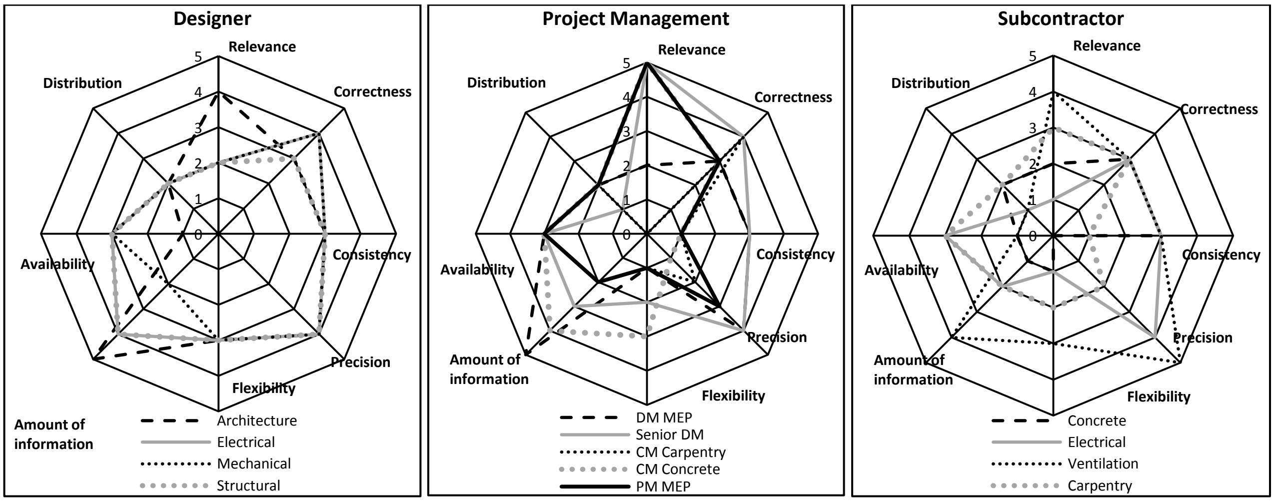

Figure 2. Radar charts of the DIQ assessments by the survey participants (CM = contract manager, DM = design manager, PM = project manager).

Three features were identified by applying the DIQ framework to the case project. First, there are only two dimensions that the participants agree on: correctness, which is generally satisfactory, with a score between 3 and 4, and distribution, with scores between 1 and 2. This result is not satisfactory and is thus an area for further improvement. Second, although the mechanical engineer and the ventilation subcontractor (a design information supplier-customer pair) and the electrical engineer and the electrical subcontractor basically agree on the level of design information quality, there is a discrepancy between the quality levels perceived by the structural engineer and the concrete contractor. This discrepancy not only indicates different perceptions of the DIQ of the information, but it also indicates a major risk that the delivered information is inadequate. Third, the assessment of three dimensions is widespread. The first dimension is the amount of information; designers provide BIM models, but a subcontractor only receives paper drawings. This indicates that the potential of BIM is not fulfilled. The second dimension is relevance; although the assessment is based on an established process in the project, the answers disagree, indicating that there is need for clarification. The third dimension is precision, which, like relevance, has a need for clarification.

4.3 Validity and Application

Before applying the framework and the questionnaire to the project, its validity was discussed with and evaluated by the project and design management teams. The framework was successfully applied to the case project; however, the successful application does not prove validity but is rather part of a validation process. The questionnaire provided meaningful assessment of the DIQ and revealed at least three areas for improvement. First, the strategy for distributing design information requires improvement. Second, the concrete contractor scores below average in almost all categories compared to the other subcontractors. Finally, the amount of information, its relevance and its precision must be addressed.

This framework contributes to the limited literature on information quality in the AEC industry (Westin and Päivärinta 2011, Tilley et al. 1997, Tilley and McFallan 2000, Andi and Minato 2003). The contributions include considering BIM and the current state of technology when studying DIQ and enabling the assessment of DIQ from the builder's perspective; providing the builder with better information quality will presumably positively influence the process and product of construction work. The dimensions, indicators and metrics are subject to discussion from both academic and practical perspectives and will be subject to further research and adjustment. However, the framework enables the measurement of the effects of BIM and other claimed improvements to project information, thereby informing the researcher which technologies and organizational settings affect the builder's basis (i.e., design information) for work and potentially leading to a better outcome for this work. The case project demonstrated the practical application of the framework by identifying areas for improvement on a real-world project. Previous work on information quality in the AEC industry has not supplied these means for understanding and assessing DIQ from the builder's perspective in the context of a construction project.

4.4 Future Research

As a whole, the proposed framework and its components require further application and validation. Making the indicators and scores operational, either through questionnaires or observation, would validate the framework. The design process planning component requires testing and evaluation in a BIM environment, in which a potential challenge may be that designers' and subcontractors' frames of reference are based on documents rather than models, objects or properties. Furthermore, the application of numerous projects will define appropriate and inappropriate DIQs and identify which methods of improvement are effective.

Additionally, the relationship between DIQ and the quality of the construction process in terms of cost overruns and delays and the final product (i.e., a building) must be established. Although dimensions and indicators remain the same over time, the metrics and scores must be adjusted to represent the current state of practice. Finally, a rigorous generalization of the documented output of the design process planning can influence the theory of planning in design. By collecting information requirements in IDMs, subsequent research can lead to the generalization of design information requirements.

5 Conclusions

This study provides a framework for assessing and improving DIQ based on eight dimensions, each associated with indicators, scores and metrics, and a technique for identifying and documenting information requirements. Although the DIQ dimensions are independent of technological developments, the scores and metrics will require regular adjustments to represent the current best possible practices as technology develops in the future.

The framework allows researchers and practitioners to compare DIQ across projects or over time on the same project. Multiple measures of the same project can provide a system for identifying areas of weakness and informational risk, as was performed for the case study. Comparing multiple projects allows one to assess whether the intended DIQ improvements had the desired effect.

Furthermore, combining design process planning and IDM provides a basis for an agreement between designers and builders to deliver better information, the means to identify the requirements, and the indicators to follow up on information delivery. A framework that focuses on and assesses DIQ provides a method to incentivize improvement, thereby increasing DIQ competition, which is currently limited. Improving DIQ for builders in the planning and execution of construction projects will eventually lead to better buildings.

Acknowledgments

The author expresses his gratitude to all of the people and companies involved in this study. The author would especially like to thank MT Hojgaard A/S for its support, the Ejnar and Meta Thorsens Foundation for funding this research and Peter Bo Olsen and Rolf Büchmann-Slorup for their valuable feedback.

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Appendix F Paper F – Assessment and Improvement of Design Information Quality on a Design-Build Project

ASSESSMENT AND IMPROVEMENT OF DESIGN INFORMATION QUALITY IN A DESIGN-BUILD PROJECT

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ABSTRACT

This study applies a framework to assess and improve design information quality in the construction of a train service station with a design-build contract. The framework consists of eight dimensions to describe the design information quality and an indicator and scores to assess each dimension. The timely delivery of relevant information is an important element of design information quality; thus, the framework is supplemented by a collaborative method to identify information requirements. First, the anticipated design information quality was assessed, and the potential problems were identified. The assessment was based on project management experience and arranged procedures. Second, based on the assessment and field observation, improvements that have been described in the literature on building information modeling were implemented in this project. Third, the implementation was followed by a questionnaire survey of 13 project participants based on the framework. This research emphasizes the practical application of the framework as a means to analyze and improve design information quality, as well as to provide guidance for improving design information quality.

Keywords: Design Management, Information Quality, Information Management, Building Information Modeling

1 INTRODUCTION

The quality of design information is not yet a competitive factor in the architectural, engineering and construction (AEC) industry. Digitalization efforts, such as building information modeling (BIM - Eastman and Siabiris 1995) and virtual design and construction (VDC - Fischer 2006), have the inherent promise of better design and design information, e.g., by the coordination of mechanical, electrical and plumbing (MEP) systems (Khanzode et al. 2008). From the builder's perspective, better design information should enable the achievement of a better outcome (e.g., fewer delays, budget overruns and building defects). Evidence from other industries suggests that information systems improve productivity (Banker et al. 2006) and that information management improves performance (Mithas et al. 2011). However, to reap these benefits, the quality of design information and its significance to builders when planning and executing construction work have to be better understood.

Quality has been defined as the *conformance to specification* (Reeves and Bednar 1994). This definition implies that the customer (i.e., builder) has requirements for a product (i.e., design information) delivered by a supplier (i.e., designer). Consequently, in this study, design information quality (DIQ) is the conformance of the information supplied by the design team to a builder's specifications for planning and executing construction work.

Information quality has been studied, assessed and measured in many industries and contexts (Ballou and Pazer 1985, Wang and Strong 1996, Lee et al. 2002). In the AEC industry, information quality has been studied by several authors. Tilley et al. (1997) study information quality using requests for information. Tilley and McFallan (2000) study information quality in the Australian AEC industry from the designer's and builder's perspectives. Their method was based on identifying problems in design information using questionnaires based on dimensions identified by experts. Andi and Minato (2003) replicated the method and concept of Tilley and McFallan's framework in a similar study of the Japanese AEC Industry. Both Tilley and McFallan and Andi and Minato report a discrepancy between the perceived DIQ of designers and builders. Westin and Päivärinta (2011) apply the Delphi method to a large engineering and construction company to study informational problems through several group interviews with professionals. Laryea (2011) analyzes the quality of UK tender documents based on ethnographic observations from two case projects. Laryea concludes that the amount of information is significant and identifies several informational problems.

Berard (2012) provides a framework for assessing and improving DIQ from the builder's perspective. The framework consists of eight dimensions describing DIQ from the perspective of the builder and an indicator and score for each dimension. The score enables each dimension to be scored in relation to the current available practice. Because the framework is based on the builder specifying requirements for the design information, it also provides a method to collaboratively identify design information requirements and document them.

The aim of this study was to apply the framework of Berard (2012) to a construction project to emphasize its applicability in practice. The intent of the framework is not only to assess DIQ but also to suggest areas of improvement. The framework is applied by assessing the anticipated DIQ. Methods and technologies from the BIM literature are then implemented to improve the DIQ of the case project. This improvement, if effective, should be measurable under the framework.

2 RESEARCH DESIGN

This research applies a framework for assessing and improving DIQ in a construction project to test the practical application. Consequently, the framework is first introduced, the case project is then described, and finally, the research method is discussed.

2.1 The Framework

The framework consists of eight dimensions (see
Table 1) of DIQ and an indicator and a score to assess each dimension (see
Table 2) according to the current stage of development. The score is based on a five-point scale from traditional practice to the most innovative practice in the AEC industry, which makes it possible to suggest improvements. It is necessary to adjust the scale regularly to capture the current state of technological development of the AEC industries. The framework is supplemented with a method to collaboratively identify information needs. The framework is derived and described in detail by Berard (2012).

Table 1: Eight dimensions of DIQ

DIQ Dimension	Description
Relevance	The scope, sequence and time frame of the information delivery.
Consistency	The coordination of design information with respect to geometry, functional requirements and compliance with standards and regulations.
Correctness	The extent of missing, incorrect, or outdated design information.
Precision	Accurate geometry and unambiguous requirements for the scope.
Availability	Effort to securely access current design information.
Distribution	Effort to manage, share and route design information.
Flexibility	Effort to transform, extract or update information for work tasks.
Amount of Information	The number of documents, files and other media should be appropriate for the scope.

Table 2: A five-point scale of each indicator used to score the dimension (1 = traditional; 5 = most innovative practice)

Dimension/ Indicator	1	2	3	4	5
Relevance/ Information flow	The builder's information needs are not identified, design in-formation is sent at the end of phases, and the sender is not able to fulfill specific information needs.	The builder's information needs are not identified, design information is sent continuously, and the sender is not able to fulfill specific information needs.	The builder's information needs are identified, design information is sent at the end of phases, and the sender is able to fulfill specific information needs.	The builder's information needs are identified, design information is sent continuously, and the sender is not able to fulfill specific information needs.	The builder's information needs are identified, design information is sent continuously, and the sender is able to fulfill specific information needs.
Consistency/ Review and coordination process	Only shared coordinates, grid, and naming conventions.	Requirements are coordinated in a collaborative process.	Geometry is coordinated using software.	Building code requirements are coordinated using software.	All functional and behavioral requirements are coordinated using software.
Correctness/ Information	Design team not available to provide	Request for information process.	Correct information achieved through an	Correct information achieved through a	Design team able to provide correct

correction process	correct information. (>4 weeks)	(1 - 4 weeks)	informal process. (5 - 7 days)	fast-track process. (3 - 4 days)	information quickly. (1 -2 days)
Precision/ Level of detail	Specifications are unambiguous.	Dimensions are sufficient for scope.	Level of detail is sufficient for scope.	BIM objects reflect production parts.	BIM objects reflect actual products.
Availability/ Digital distance	Paper documents at the office.	Digital documents at the office.	On a notebook.	Digital at the place of production.	On a mobile device.
Distribution/ Information distribution	Broadcast (information push).	Receiver chosen manually (information push).	Receiver chosen by role (information push).	Receiver subscription (information pull).	As specified by information requirements (information pull).
Flexibility/Design information medium	Documents.	Editable documents.	Geometrical 3D models.	BIM models.	BIM models according to information requirements.
Amount of information/Medium of design information.	Documents.	Digital documents (not versioned).	Digital documents (versioned).	Multiple 3D models and specifications.	Integrated 3D models and specifications.

The method used to collaboratively identify information requirements is based on a method by Ballard (1999) that adjusts the phase scheduling (Ballard 2000, Ballard and Howell 2003) to the design. Phase scheduling applies pull techniques and team planning. Ballard (1999) concludes that "*joint assignment of design tasks to both provider and puller both promotes common understanding of criteria and also ensures that resources are used first to do work that is needed now by someone else".* The phase scheduling for design is adjusted to include the identification of detailed information needs. Design phase scheduling was used in a case study (Ballard 2002). In this research, the design phase scheduling serves as an input to the design structure matrix (DSM) method, which is a method used to identify the best sequence of design tasks (Browning 2001, Koskela et al. 1997).

2.2 The Case Project

The case project is the design and construction of a 10,000-m^2 train service station, with a design-build contract of approximately €36 million. The design phase is eight months, and the total design-build period is expected to be 2.5 years. Design and planning are parallel activities, and the procurement and scheduling of construction are concurrent with design. The design team and project management are collocated at the construction site office.
In this study, the following three groups of actors are studied: the design team (information supplier), the builder's project management (information consumer) and the subcontractors (information consumer). It was chosen to focus on four trades: carpentry, concrete, electrical and ventilation. The representatives involved in the study and their preferred medium for creating or viewing design information are shown in
Table 3. Design information is shared through a project website.

Table 3: Role (**bold**) and design information medium (*italics*) of survey participants according to trade

	Subcontractor	General contractor	Design team
Carpentry	**Project manager** *Drawings*	**Contract manager & senior design manager** *Drawings*	**Architectural manager** *BIM*
Concrete	**Project manager** *Drawings*	**Contract manager & senior design manager** *Drawings*	**Structural manager** *BIM*
Electrical	**Project manager** *2D CAD*	**Project manager & design manager** *Drawings*	**Electrical manager** *BIM*
Ventilation	**Project manager** *BIM*	**Project manager & design manager** *Drawings*	**Mechanical manager** *BIM*

2.3 Research Method

In this study, the researcher became actively involved by following and facilitating design and planning activities. This involvement led to the suggestion of improvements for the organization being researched (Hartmann et al. 2009, Somekh 1995). Consequently, there is a distinction between the research method, described here, and the development procedure (cf. section 3). The researcher followed the design and planning of the project from the early beginning to the start of construction. During that time, data were collected by participation in meetings and workshops, observations of practice, unstructured and semi-structured interviews and discussion with project participants, and a follow-up questionnaire survey. The output was documented by notes and memos, pictures, and slide presentations. Furthermore, design planning tools, such as meeting minutes, to-do lists, design schedules, requirement control documents, and design output, such as drawings, specifications and 3D models, were reviewed. These data are used, to challenge and follow-up on the practice. Together with the project and the design management, three major areas of improvement were identified through the application of the framework.

As a follow-up, 13 questionnaire interviews, four with designers, five with design and project managers and four with subcontractors, were conducted to assess the DIQ. The method of the interview survey is based on Bloom and Van Reenen (2010), who suggest using open questions to avoid interviewee bias and letting the interviewer make an assessment based on the answers. The outcome of the survey is visualized in a radar chart.

3 DIQ IMPROVEMENTS

The framework was applied early in the project through the assessment of the anticipated DIQ by the project management (see Figure 1). The assessment of the project was low overall; as a consequence, the DIQ should be addressed in multiple areas. The project management and the researcher chose the following three main areas to improve: (1) design phase planning to influence relevance (DIQ dimension); (2) design review to influence consistency and correctness; and (3) BIM communication to subcontractors to influence distribution, availability, flexibility and the amount of information available.

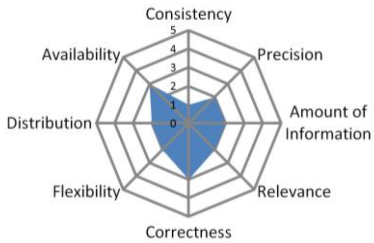


Figure 1: Assessment of anticipated DIQ by the project management

To identify the current practices in the three areas, the researcher participated in the work of the project team. Applications were identified by relating the observations of the current state to the methods and technologies from the BIM literature. BIM methods and technologies are implemented and practice is changed to obtain a measurable DIQ improvement for this study.

3.1 Design Phase Scheduling

In the following section, the observations, suggested improvements and effects on practice are described for each of the following areas: design phase planning, design review and BIM communication to subcontractors.

3.1.1 Current State

Initially, the design is planned through the client's list of drawings. A design schedule exists, and that consists of one entry for every discipline (architecture, structure and MEP design) for both phases (i.e., detailed design 1 & 2) and milestones for internal and client reviews. Because the schedule is light, planning is conducted during design meetings. In this project, there were two types of design meetings: design meetings with the design team, project management and subcontractors and design meetings without subcontractors.

The objective of the design meetings is to coordinate technical solutions; however, a substantial amount of time is spent discussing practicalities and requesting missing information from designers, project management, the client and municipalities. The missing information is captured in the meeting minutes and a comprehensive to-do list, which are scrutinized at each meeting. The design meetings are seldom conducted within the assigned time of two hours. Scheduling is performed during the meetings by either setting deadlines for information or decision requests or discussing the final deadline.

The primary argument put forward for not planning the design more thoroughly is the iterative nature of design. Design is inherently new and unknown and has a high variability, which allegedly entails that the duration of the design task cannot be estimated. Schedule control is performed by design discipline manager who either encourage the team to work extra hours or request additional resources.

3.1.2 Intervention

Together with the design management, it was decided to implement design phase planning as described by Ballard (1999) and Ballard and Howell (2003). In this way, information requests from subcontractors and designers can be handled proactively, and a prioritized design schedule that supports the informational flow can be provided. Two workshops were held, one for each type of design meeting, and facilitated by the author. Each workshop participant filled in one post-it note for each informational product that typically is delivered and, more importantly, the information this product requires from others. The informational products are building components based on the object structure of a BIM model instead of drawings. After having filled in the post-it notes, the design information and design sequence were pulled; starting from the final task (i.e., drawings for approval by the municipality) each participant reported the information required from others; the others subsequently reported their information needs.

3.1.3 Effect

After both workshops, there was strong anecdotal evidence that the participants were very satisfied with the process and the outcome. The participants had the possibility to express information needs, and there was a better understanding of the information needs of others. The output of the workshop resulted in an update of the design schedule, which became more detailed than the former by referring to the design of sub-systems. However, design phase scheduling did not become included in the practice of design management, and the identified detailed sequence did not become part of the design schedule.

3.2 Design Review

3.2.1 Current State

According to the quality management systems standard (ISO 9001) of the international organization for standardization (ISO), the purpose of design and development review is *to evaluate the ability of the results of design and development* (i.e., design information) *to meet requirements, and identify any problems and propose necessary actions*. The design review is both an individual in-depth check on whether requirements (e.g., from the client, occupants or municipality) for the design are fulfilled (East et al. 1995) and a collaborative review by multiple stakeholders from different perspectives (Elioff and Edgerton 2004).

The design review, as an in-depth check of requirements, was based on self-inspection and quality assurance by coworkers. Furthermore, a design requirement matrix was used to keep track of client, regulatory and legislative requirements. The coordination of MEP systems was primarily subject to self-inspection and quality assurance by coworkers. Clashes were visually checked by overlaying drawings and BIM models in software programs. Software-based model checking was expected to occur at the end of, rather than regularly during, the design phase.

Collaborative design reviews are held regularly with different scopes. The purpose of the reviews is to ensure that drawings from different disciplines are consistent and contain the necessary information. The topics discussed in review meetings included geometrical coordination, missing details, technical solutions and municipal requirements. At the observed meetings, several designers from all disciplines, as well as design and project management, were present. Before a design review meeting, all necessary drawings are printed. At the meeting, the drawings to be reviewed are put on a whiteboard (see Figure 2). The drawings are compared and reviewed, and notes are taken on the paper drawing. The drawings are then given to the respective design discipline managers to follow up on the issues identified. There are several problems with this process, as identified by observations and follow-up interviews. The following identified problems were mostly practical: multiple drawings cannot be held with a magnet, it is difficult to physically switch between drawings, and there are problems with the distribution and documentation of the review comments and the time it takes to print drawings before the meeting.

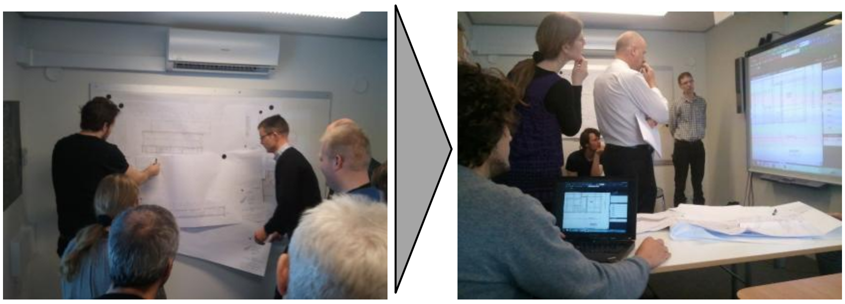


Figure 2: Design review, both traditional (left) and with an interactive whiteboard (right; photography by the author)

3.2.2 Intervention

The coordination of MEP systems with digital 3D models is a common area of automated checking in research (Khanzode et al. 2008, Staub-French and Khanzode 2007, Leite et al. 2011) and practice (DiKon 2012). Khanzode (2010) proposes a method for the coordination of MEP systems based on six steps. First, strategic goals and specific objectives are defined. Second, a multi-disciplinary team is formed. Third, specific metrics to track progress and to measure outcomes are identified. Fourth, technical logistics for management are determined. Fifth, a pull schedule is created. Sixth, operation and management are measured against the objectives, making adjustments and measuring outcomes and results. In the case project, a BIM coordinator was appointed who, together with the researcher, implemented a process based on that proposed by Khanzode (2010).

Information technology can also support the collaborative design review. Research is focused on enabling the AEC professionals and non-domain experts, e.g., clients and occupants, to interact with and discuss a virtual mockup (i.e., 3D design model) (Shen et al. 2012, Aspin 2007, Shiratuddin and Thabet 2003, Dunston et al. 2011). The iRoom is an environment designed for collaborative meetings that consists of multiple interactive whiteboards and the controlling software (Johanson et al. 2002). To better facilitate the design review meetings, project management bought two interactive whiteboards. These whiteboards were not placed side by side as in the iRoom but rather in two different meeting rooms.

3.2.3 Effect

Anecdotal evidence and observations suggest that the coordination of MEP systems is very functional. Design coordination is conducted on a regular basis, and designers receive feedback on clashes between MEP and other building systems. It was even requested by the design management, who were skeptical at first, to conduct coordination with more systems than initially agreed upon. The structure of collaborative design reviews did not change substantially after the implementation of the interactive whiteboards, but the practical problems were easily addressed, which improved the efficacy of the meetings.

3.3 Communicating Design to Subcontractors

3.3.1 Current State

The third area of intervention is the communication of design information to subcontractors. Usually, subcontractors receive piles of documents. In this project, it was decided early on to encourage subcontractors to engage in a digital work flow, which is why drawings and specifications were only available digitally to subcontractors. Figure 3 shows an example of manual quantity take-off compared with a digital-based drawing and a digital information take-off model.

3.3.2 Intervention

It is trivial to note that replacing paper drawings with digital documents reduces printing costs. To increase efficiency, it is necessary to adjust work procedures to facilitate a digital process. However, the reduced printing cost was a reason for the intervention, and savings are expected to be €100,000 on this project.

Berard and Karlshoej (2012) suggest giving digital information take-off models to subcontractors (see Figure 3, right). However, the contract manager determined that the models did not have the necessary content for this purpose. They needed an upgrade by the design team, which was not possible to achieve within a reasonable time due to contractual issues. Obviously, the interactive whiteboards are also being used to discuss designs with subcontractors. It was also decided to encourage the use of mobile devices during construction to view design information. Mobile devices were preferred over iBooth (Ruwanpura et al. 2012) because they provide access to digital information directly at the place of work.

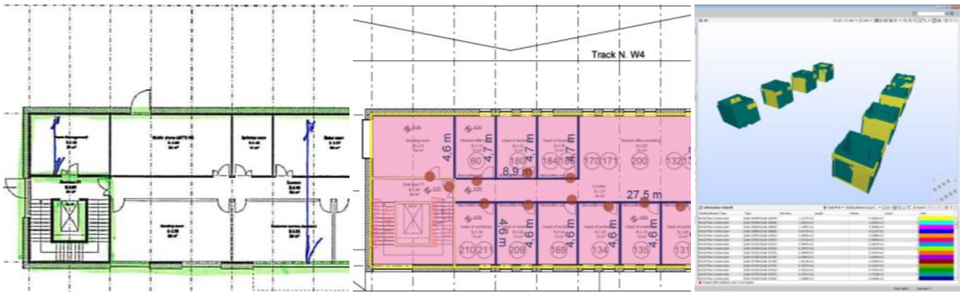


Figure 3: Examples of manual quantity take-off (left), digital quantity take off (middle) and a quantities model (right; screenshots courtesy of MT Hojgaard)

3.3.3 Effect

Only the design and planning phase was observed in this study, during which digital documents were shared with the subcontractors. Whether the subcontractors will choose to work digitally or print the digital drawings is unknown. It was intended to use the interactive whiteboards and mobile devices during construction.

4 RESULTS AND DISCUSSION

The results of this research are two-fold. First, remarks and implications regarding the case project arose from the application of the framework. Second, the applicability and utility of the framework to assess and improve DIQ in general can be discussed based on its application. After discussing the results, future research will be addressed.

4.1 Implications of the Case Study

A comparison between the assessment conducted before the interventions (see Figure 1) and the average scores given to the project after the interventions (see Figure 4) indicates that the dimensions of consistency, precision, amount of information and relevance were subject to significant improvements. The correctness and flexibility improved slightly while the distribution and availability decreased slightly, which indicates that the overall DIQ increased post-intervention.

The assessment by the design team, project management and subcontractors is shown in Figure 4 and Figure 5. The overall assessment by the design team is homogeneous; in particular, the engineering disciplines are closely related, and the architect’s assessment of DIQ is better than the assessments by the other designers along almost all dimensions. The assessment by project management is not convergent but, in general, above average. The assessment by the subcontractors is very heterogeneous, which is not contradictory because every subcontractor has an individual setting of design information. Ventilation contractors assigned the highest DIQ score; this is potentially related to their proactive work in the design and use of BIM models. Meanwhile, the concrete and carpentry subcontractors assessed the DIQ very low, while the electrical subcontractors provided an average assessment of the DIQ. The focus of project management should be on the carpentry and concrete subcontractors because a low DIQ can indicate a risk to the project outcome. Based on a comparison of the designers and subcontractors, again, the difference between the assessments of the carpentry and concrete subcontractors (receivers) and the architects and structural engineers (senders) has to be noted and should be addressed by project management.

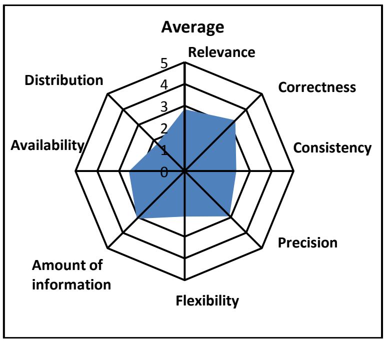
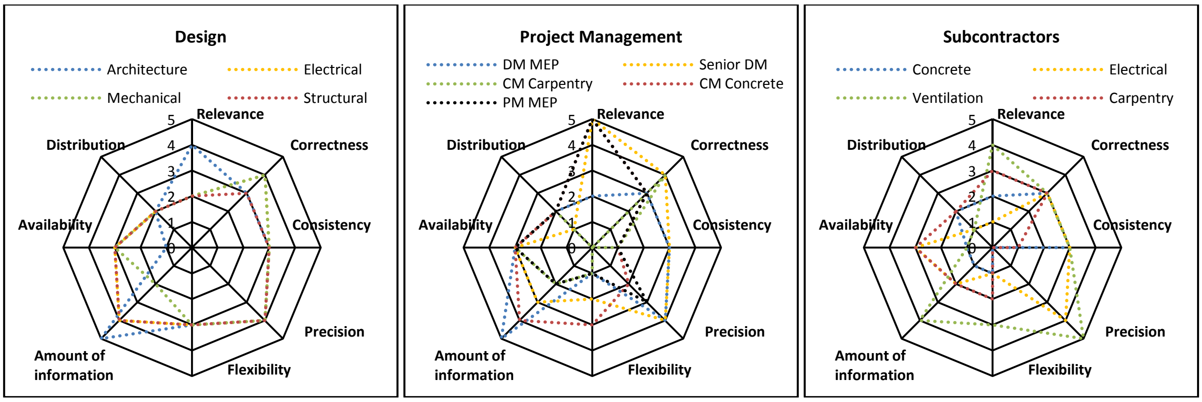


Figure 4: Radar chart of the average DIQ assessment by all project participants



CM = contract manager, DM = design manager, PM = project manager

Figure 5: Radar chart of the DIQ assessment according to role on the project

4.1.1 The Individual Dimensions

In this section, the assessment of each DIQ dimension is discussed separately. The order of the discussion is from the most to least controversial.

Responses associated with the dimension *amount of information* are widespread. Even though designers provide BIM models with more than only geometric information, one of the subcontractors only receives paper drawings. Subcontractors and designers are not sure they work with the right version of the design information. The occurrence of designers using BIM models and subcontractors working with paper documents is not contradictory but could be an indication of a lack of competence of the subcontractors in making use of the models.

The assessment of *relevance* is particularly interesting; it is based on the project practice, but the outcome is very heterogeneous. The project and design management assume a high degree of relevance. However, both the designers, except the architect, and the subcontractors, except the ventilation contractor, experience a low degree of relevance. After being asked, the architect ensures a high degree of relevance through close contact with the subcontractors, which, however, cannot be observed based on the assessment of the carpenter. Overall, relevance is an area for improvement, which is congruent with the observation of design process planning.

Due to the state of progress of the project, the score of *precision* does not necessarily have to be greater than three. However, both the designers and subcontractors experienced an even higher degree of precision, except for the concrete and carpentry subcontractors, who scored very low due to imprecise specifications.

The dimension of *flexibility* is closely related to the amount of information. However, while the amount of information measures the information medium that is used for the work, flexibility measures the potential of having access to BIM models. The effect of the potential access becomes visible in that the MEP design manager assigns divergent scores to amount of information (i.e., one) and flexibility (i.e., five); the MEP design manager has access to BIM models, but does not use them. For the other participants flexibility and amount of information are related; there is a maximum score of three because only geometry is communicated by BIM models. Generally, the designers send building models, but project management and subcontractors do not use them.

For *availability* of information, most respondents had access to the information through notebooks, which also facilitates discussion at design information meetings, and only a few had access at the office. A higher level of availability is desirable for construction work.

There is almost unanimous agreement that *consistency* is reached through software-supported MEP system coordination. This measure is objective, and a standard procedure for MEP coordination was established during the project. Surprisingly, not all of the study participants were aware of it and therefore provided a lower assessment of the project.

Correctness is established by a straight-forward process. The difference in the scoring is only due to a few days of the designers' response time, and the designers are expected to answer more quickly than is perceived by the project manager and construction managers. In general, the correctness is satisfactory.

Distribution, the way in which project information is shared, is generally assigned low scores, particularly by participants who are not part of the general contractor's organization, which includes the architect and the electrical and ventilation contractors. This score points to an area for further improvement.

4.1.2 DIQ Problem Areas

The dimensions amount of information, relevance and precision are assessed with widespread disagreement, which indicates the need for further discussion and treatment to at least reach agreement. The concrete subcontractor probably needs help to raise his/her DIQ, which is in the interest of the project because it reduces risk. The project website is not well suited to distribute design information. Project management is aware of this issue; however, they decided that the IT system cannot be easily replaced during an ongoing project.

4.2 Application of the Framework

The framework can provide an indication of problem areas of DIQ in different ways. First, the difference between the assessments of the suppliers and consumer of design information indicates a problem, which is especially the case when the designer assumes a higher DIQ than the subcontractors. Second, an overall low score of a dimension indicates a common problem that needs to be addressed. Third, a very heterogeneous assessment of a dimension indicates that the clarification of established practices is needed at the very least. The application of the framework to the project yielded these areas of discussion.

The application has also indicated components of the framework that need to be noted in subsequent uses of the framework. The framework aims to be applicable during design, planning and construction; however, the dimensions of precision and availability have different desirable maximum values depending on the project phase. Precision typically increases over time, and availability during construction is increased at the work site. This problem could be solved by assigning different scores (cf.
Table 2) to each phase; alternatively, a maximum score lower than five could be acceptable during earlier phases. It is also important to clarify for the survey participants that the assessment is based on the current state and not a future state, which was a recurring question posed to the research assistant. According to the framework, unambiguous specifications are of major concern with regard to the precision dimension. This fact results in low scores due to ambiguous specifications even though the precision of other scores is consistent with a satisfactory DIQ. Ambiguous specifications are a problem for builders, who need to know what should be procured. However, the influence of such ambiguous specifications influence on the assessment is high and should at least be noted.

4.3 Future Research

The framework and the questionnaire will mature through their further application. Their application to more projects and more assessments is necessary to improve the framework and its impact on practice and research. Furthermore, prioritizing the dimensions of DIQ would help to visualize the results of the DIQ assessment. The radar chart provides an overview of the DIQ assessment; however, by expressing DIQ with a single meaningful value, the data from a large number of projects could be analyzed. Relating DIQ to unintended outcomes of construction work, such as schedule delays, cost overruns and building defects, can provide valuable insights on the relation of unintended outcomes and DIQ.

5 CONCLUSION

The framework implemented to assess and improve DIQ has been applied to a construction project, and its practical value has been demonstrated. It was shown that the framework is suited to highlighting problem areas and suggesting improvements for these areas. However, the framework, as well as its dimensions, indicators and scores, should be subject to academic discussion and research to validate and improve them. The framework is not a detailed configuration but rather a means of addressing and discussing the use of DIQ in practice and a means of analyzing the effect of BIM and other improvements.

6 ACKNOWLEDGEMENTS

The author would like to express his gratitude to all of the people and companies involved in this study. I would especially like to thank MT Hojgaard A/S for its support; the design and build team of the case study, especially the project manager Malte Fryd; the Ejnar and Meta Thorsens Foundation for funding this research; and Peter Bo Olsen and Rolf Büchmann-Slorup for their valuable feedback.

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List of Abbreviations

AEC: Architectural, Engineering, and Construction
AIA: American Institute of Architects
ANT: Actor Network Theory
BIM: Building Information Modeling
BPMN: Business Process Mapping Notation
CAD: Computer-Aided Design
IDM: Information Delivery Manual
IFC: Industry Foundation Classes
ISO: International Organization for Standardization
MPS: Model Progression Specification
MVD: Model View Definition
IPD: Integrated Project Delivery
IS: Information Systems
IQ: Information Quality
PRQ: Preliminary Research Question
RFI: Request for Information
RQ: Research Question
SCOT: Social Construction of Technology
STS: Science-technology-society
SSK: The sociology of scientific knowledge
T#: Research Task #

Acknowledgements

I am truly indebted and thankful to several people, without whom this research would not have been possible.

Flemming Vestergaard, Associate Professor, Principal Advisor
For his guidance and support.

Jan Karlshøj, Associate Professor, PhD Advisor
For sharing many of his invaluable contacts with me, many of which have inspired this research.

Lars Fuhr Pedersen, Head of Section, Company Advisor
For giving me the opportunity to pursue my research interest.

Martin Fischer, Professor, Visiting PhD Advisor
For fruitful discussions and welcoming me into his research group.

Peter Bo Olsen, BIM Manager, Unofficial PhD Advisor
For his support that helped me finish on time.

Rolf Büchmann-Slorup, PhD student
For valuable feedback and discussions, and for being a good travel companion.

Christine Thorsen and the Ejnar and Meta Thorsen Foundation
For funding my research.

The Danish Agency for Science, Technology and Innovation
For funding my research.

Niclas Andersson, Kristian Kreiner and Arto Kiviniemi, PhD Committee
For serving on my evaluation committee.

Jens Nyhus, Niels Falk, Niels Kjeldgaard and Peter Kofoed, PhD Reference Board
For regularly discussing my findings.

I would also like to thank Malte Fryd (MT Hojgaard), Tore Hvidegaard (3dbyggeri Danmark), and Atul Khanzode (DPR Construction).

Furthermore I would like to thank my co-workers at MT Hojgaard and construction practitioners I visited in Denmark, all over Europe and the USA for participating in my research – none mentioned and none forgotten.

Lillian, Johanne and Viktor Berard, my family
For your support and patience during the last three years.

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Contractors receive insufficient design information to plan and execute construction work. Recently, building information modeling has grown in popularity and has the inherent promise of better design information quality. However, design information quality itself has not received a much attention. In order for it to improve, it must be understood from the information consumer's perspective and be made measurable to assess progress. Consequently, this thesis provides a model that describes design information quality from the contractor's perspective and a method for measuring design information quality for practice and research.

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ISBN: 9788778773548
ISSN: 1601-2917